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AN INVESTIGATION OF THE EFFECT OF SURFACE FINISH
ON THE FLEXURE FATIGUE STRENGTH OF 75S-T6
ALUMINUM ALLOY SHEET

A THESIS

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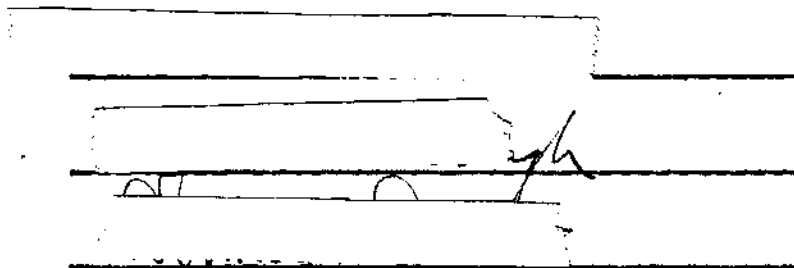
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Approved:

The signature block contains several horizontal lines. A handwritten signature, possibly 'J. H. ...', is written across the middle lines. Below the signature, there are some faint, illegible markings that appear to be initials or a date.

Date Approved by Chairman

Nov. 4, 1949

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SUMMARY

Flexure fatigue tests have been conducted for Alclad 75S-T6, 75S-T6 and 24S-T3 sheet of commercial thickness 0.040 inches for polished specimens, and specimens scratched by various abrasive cloths. Curves of applied stress versus number of cycles to failure have been plotted, and stress concentration factors for the individual materials and abrasive grits determined. The flexure fatigue strengths of the materials have been compared, both in the polished and scratched states, and conclusions have been drawn concerning the relative merits of the different materials with respect to their fatigue qualities.

INTRODUCTION

The study of fatigue has become more important each year. The S-N curves, or Wohler curves as they are called in the German literature, where the number of cycles to failure (N) is plotted as a function of the stress (S), of many different materials have been determined and published. More recently, fatigue studies have been carried out to determine the effect of certain stress raisers such as holes, notches, and fillets on the fatigue strengths of certain materials. For aluminum alloys, with which the aeronautical engineer is especially concerned, the data are meager and, for the recently developed high strength aluminum alloys, are practically non-existent.

The design of aircraft elements has been based upon certain limit loads which are rarely, if ever, encountered. To these, a small margin of safety is added to determine the design loads. However, as the loads on the structure, and consequently the induced stresses, can be considered as consisting of a steady, or dead load, and a superimposed dynamic load, the opportunities for fatigue failures should not be overlooked.

It has been claimed by some that the fatigue failures which have occurred in the past have not been serious in nature. Before 1939, there were no cases on record in which

a wing spar failure was caused by fatigue.¹ However, it seems likely that such failure could possibly have occurred without being detected. More recently failures of this nature have occurred, and with great loss of life.² Fatigue failure in propellers and tail assemblies have also caused many fatal accidents.³

The factors which contribute to fatigue failures have by their nature made the problem more acute each year in spite of the more advanced understanding of the conditions for failure. Some of the factors are: higher speeds, increased wing loadings, increased fire power and maneuverability, pressurized cabins, and radical design changes such as jet and rotary-winged aircraft.⁴

The use of new material with higher static ultimate strength, but not proportional increase in fatigue strength

¹Arnstein, K., Shaw, E.L., "Fatigue Problems in the Aircraft Industry", Metals and Alloys, 10:203-9, July 1939.

²Anonymous, "2-O-2 Report," Aviation Week, 49:26, October 1938.

³Staff of Battelle Memorial Institute, Prevention of the Fatigue of Metals Under Repeated Stress (New York: John Wiley and Sons, Inc., 1941).

⁴Jackson, L.R., Grover, H.J., and McMaster, Battelle Memorial Institute, "Advisory Report on Fatigue Properties of Aircraft Materials and Structures," War Metallurgy Committee, OSRD No. 6600, Serial Number M-653, March 1, 1946.

has also been a contributing factor. This is particularly true in aircraft since the great majority of parts are designed to operate at a certain percentage of their ultimate strength. Consider the case of two materials with equal endurance strengths, but with unequal ultimate strengths. A certain percentage of the lower ultimate strength for the one material might result in a working stress less than the endurance strength, while the same percentage of the higher ultimate strength of the other material could conceivably result in a working stress greater than the endurance strength. In aircraft use, the aluminum alloys 75S-T6 and 24S-T3 are materials with physical properties similar to the above condition. The 75S-T6 is the newer of the two alloys and has the higher ultimate strength.

The purpose of this investigation is to determine the effect of surface finish on the fatigue strength of 75S-T6 and to compare this effect with that of similar stress raisers on 24S-T3.

MATERIAL

The materials used for the fatigue tests were Alclad 75S-T6, 75S-T6 and 24S-T3. The Alclad sheet had a core material of the specified alloy and a surface cladding of practically pure aluminum on each side. For this type, the word Alclad has been used as a prefix to the alloy designation. The other sheet material had no cladding on the surface. This, in some literature, is sometimes referred to as "bare". In this report, however, the alloy designation with no prefix indicates that the material was not of the clad type. This notation has been followed consistently throughout the report.

The nominal composition of 75S is 1.6 per cent copper, 2.5 per cent magnesium, 5.6 per cent zinc, and 0.3 per cent chromium. The balance is aluminum and normal impurities. For the alclad sheet, the core is 75S and the cladding material is 72S, which has a nominal composition of 1 per cent zinc, with the remainder aluminum and normal impurities. Alloy 24S nominally consists of 4.5 per cent copper, 0.6 per cent manganese, 1.5 per cent magnesium, balance aluminum and normal impurities.⁵

⁵Anonymous, Alcoa Aluminum and Its Alloys (Pittsburgh, Penna: Aluminum Company of America, 1947), p. 85.

Following the alloy designation, are the heat-treat symbols. The "T" indicates the alloy to be of the heat-treatable type, and the number indicates the heat-treat process. The final properties of the materials are determined by this process. For 75S-T6, the number six indicates a solution heat-treat followed by artificial aging. On 24S-T3, the three indicates a solution heat-treat followed by strain hardening, which in the case of sheet, comes about in a flattening operation.

All of the sheet used throughout the tests was of the commercial thickness 0.040 inch. The actual average thickness varied from 0.0390 inches for the Alclad 75S-T6 to 0.042 inches for the 75S-T6. Although the thickness of the individual sheets varied a few ten thousands of an inch from the actual average, all calculations and machine settings were made on the basis of a constant thickness for each individual sheet. One series of tests for polished specimens alone was run on 0.032 inch thick Alclad 75S-T6.

Mechanical properties of the alloys used are shown in Table I. These were determined from tension tests on standard specimens of two-inch gage length.⁶ The values

⁶Davis, H.E., Troxell, G.E., and Wiskocil, C.T. The Testing and Inspection of Engineering Materials, (New York: McGraw-Hill Book Company, Inc., 1941), p. 80.

represent an average of two tests for each material. The average stress-strain curves for the materials used are shown in Figures 1, 2, and 3.

THE FATIGUE TESTING MACHINE

The machine with which the tests were conducted was a Sonntag Flexure Fatigue Machine, Model SF-2, shown in Figures 4, 5, and 6. It was of the constant repeating force type, acting on a cantilever specimen designed to give a constant bending stress throughout the test section. The varying vertical shear stress was neglected as is customary with this type loading. The speed of loading was 1800 cycles per minute.

The operation of the machine has been very well described in previous theses.^{7,8}

THE FATIGUE SPECIMENS

The layout of the fatigue test specimen, along with mounting details, is shown in Figure 7. The specimen was mounted as a cantilever and was designed to produce a constant bending stress in the area bounded

⁷Bond, A.C. "Fatigue Studies of 24S-T and 24S-T Alclad Sheet with Various Surface Conditions" (unpublished Master's Thesis, Georgia Institute of Technology, Atlanta, Georgia 1948), p. 5.

⁸Duchacek, Howard, "A Study of the Effect of Thickness on Fatigue Strength of 24S-T3 Aluminum Alloy Sheet" (unpublished Master's Thesis, Georgia Institute of Technology, Atlanta, Georgia 1948), p. 7.

by the two straight non-parallel lines and their intersection with the three-eighths of an inch radii.

Preparation of Specimens: The aluminum sheet was cut into rectangles on a manually operated shear. The length of the rectangle was three and one sixteenth inches, and the width was two inches. The holes were drilled in the jig (shown in Figure 8), and the test section cut out on an Onsrud routing machine, as per Figure 7. The long dimension of the rectangle was in all cases, in the direction of rolling for the sheet. The tensile and compressive forces produced by the flexure machine therefore acted in the direction of the grain of the material. The tool marks on the edges of the straight sides bounding the test section and the adjoining radii were removed by polishing with 240 grit aluminum oxide cloth, backed up by a three-eighths inch diameter wooden dowel. This served to keep the edge square and perpendicular to the flat surface of the sheet. The edge was then polished in the same manner with 400 grit aluminum oxide cloth. By first using a new piece of abrasive to polish out the major scratches, from the previous abrasive cloth, and then a "used" piece of the 400 grit cloth⁹, the edge looked absolutely smooth to the unaided eye.

⁹Gallaher, E.B. Coated Abrasives, A Handbook and Digest of Coated Abrasives Technology (Norwalk, Conn: Clover Manufacturing Company, 1945) 36 pp.

However, to ensure that the edges were as well polished as practical, all specimens were inspected during and after the polishing operation under an eight power magnifying glass. From this, and the fact that all specimens were polished by the author, it was felt that the edges were uniform and contained no major scratches.

In the course of processing, the surface of the alclad specimens became very slightly scratched. Within the area of the test section, minor mars were removed by buffing in the direction of rolling. No attempt however, was made to remove all scratches, and the change in thickness due to buffing could in all cases be neglected. In instances where a remaining scratch was considered important, a note was made of the location. If the fatigue fracture occurred at this position, the test point was disregarded. The surfaces of the 75S-T6 and 24S-T3 specimens were also buffed in order to make the tests as consistent as possible.

Application of Scratches: On the Alclad 75S-T6, the scratches for the various tests were made with crocus cloth and 100 and 60 grit aluminum oxide abrasive cloths. Aluminum oxide 60 grit abrasive cloth was used for the 75S-T6 and 24S-T3 specimens.

For all specimens, a strip of abrasive cloth

approximately one-half inch wide, was held by hand and with slight pressure, drawn across the specimen test section several times in an attempt to produce a uniform number of scratches on the test section. This was done to each side of the specimen, using a new piece of abrasive cloth for each side and each specimen. All scratches were made in a direction perpendicular to the center line of the specimen.

This particular method of imparting the scratches to the specimen, and the use of the above mentioned abrasive grades, was chosen in order to make a notch sensitivity comparison of the two alloys 75S and 24S with as few variables as possible. The experimental program for 24S has been previously conducted by Bond.¹⁰

Depth and Nature of Scratches: In order to determine the depth of scratches, the specimen test section surface was examined with the aid of a Baush and Lomb Research Metallograph. For the specimens scratched with the finer grades of abrasive, a magnification of about X2000 was used. For those specimens scratched with number 60 grit, a magnification of about X1000 was used. This reduction in magnification was

¹⁰Bond, op. cit., pp. 1-30.

necessary since a scratch made by 60 grit covered the complete field of vision at X2000 and the depth could not be measured at the higher magnification without moving the specimen.

The actual measurements were made by first centering the scratch in the field of vision. The microscope was then focused on the level surface adjacent to the scratch. The reading on the focusing knob was noted. The microscope was then focused on the bottom of the scratch. The reading was again noted. The difference between the two readings on the calibrated vertical focusing knob gave a direct measure of the depth of scratch.

The actual scratches varied in depth, width and cross-section shape. This was expected, since for any one abrasive number, the particles vary to some extent in size and shape.

The observed depths ranged from some hardly noticeable up to a certain measured maximum for each abrasive. A determination of average depth over so great a range would not give a true picture of the stress concentration factor operative in fatigue failure. Further, an average of this nature would tend to associate a certain stress concentration factor with a certain average depth and this average, being composed of many lesser scratches,

would be a depth smaller than the major scratches which are most likely to cause failure, other factors being equal. Thus, it would then appear, that a smaller depth of scratch possessed a damaging effect more severe than in reality. In view of this, only the maximum depths observed are recorded in Table II. No doubt, some depths were greater than these, and many slightly less. The values serve more to establish the magnitude than the exact numerical depth in inches.

TEST PROCEDURE

The stress applied to each specimen was determined by the setting of the eccentric mass, shown in Figure 4. Sample stress calculations and machine setups are given by Bond¹¹, Duchacek¹², and in the operating instructions for the machine¹³. The eccentric mass setting was made before the specimen was placed in the machine. This was done to ensure that the specimen would not be bent or twisted. The test specimen was inserted with its center line perpendicular to the fixed mounting, and the movable yoke was set

¹¹Bond, op. cit., pp. 9-10.

¹²Duchacek, op. cit., pp. 10-11.

¹³Anonymous, "Instructions For Installation, Operation, and Maintenance of Flexure Fatigue Testing Machine, Model SF-2" (Greenwich, Conn: Manual furnished by Sonntag Scientific Co., July 1948) p. 4.

parallel to the fixed mounting. This eliminated any possibility of unsymmetrical loading.

The following tests were conducted:

<u>Test Number</u>	<u>Alloy</u>	<u>Surface Condition</u>	<u>Thickness In Inches</u>
1	Alclad 75S-T6	Polished	0.032
2	Alclad 75S-T6	Polished	0.039
3	75S-T6	Polished	0.042
4	Alclad 75S-T6	Scratched by Grocus Cloth	0.039
5	Alclad 75S-T6	Scratched by 100 Grit	0.039
6	Alclad 75S-T6	Scratched by 60 Grit	0.039
7	75S-T6	Scratched by 60 Grit	0.042
8	24S-T3	Polished	0.0395
9	24S-T3	Scratched by 60 Grit	0.0395

Since the specimen edges were polished by hand and the scratches were applied by hand, it was realized that not all specimens for any one test would be exactly the same, especially since no more than two or three specimens were given the final surface finish each day. In order to minimize the effect of this difference in specimens from day to day, if there were any such effect, the test points were not run in order of increasing or decreasing values of stress. In other words, one speci-

men was run at a high stress, the next at a low stress and the next perhaps at some intermediate value. This procedure gave test points throughout the complete curve and any difference in specimens would add to the scatter of points on the complete curve rather than establish a false trend.

In general, a maximum stress setting of about 45,000 pounds per square inch was used to determine the lower limit of stress applications, and an upper limit of 10 million cycles was arbitrarily taken. With the machine running continuously, approximately four days were required to complete 10 million cycles of completely reversed stress. If the specimen remained unbroken after that number of cycles, the machine was stopped and the point plotted as a horizontal arrow, the ordinate of which indicates the stress setting with the arrow origin located at the number of cycles actually completed.

DISCUSSION OF RESULTS

Alclad 75S-T6: The S-N curve for polished Al-clad 75S-T6, 0.032 inches thick is shown in Figure 12. Also plotted are the tests points for the polished Al-clad 75S-T6, 0.039 inches thick. A comparison of these data reveals that for the small difference in thickness, there is little or no difference in the fatigue strength.

A similar conclusion for 24S-T3 was drawn by Duchacek¹⁴ in his investigation of size effect on that alloy.

Figure 13 is an S-N plot of Alclad 75S-T6, 0.039 inches thick, in the polished state and scratched by crocus cloth. The curve for the polished specimens is repeated on each figure in order to measure the damage caused by each of the various abrasive grades. Figures 14 and 15 show the S-N curves for the Alclad 75S-T6 scratched by numbers 100 and 60 grit. A comparison of results for the various surface conditions is shown in Figure 16.

75S-T6: Figure 17 shows the result of test made on 75S-T6 of thickness 0.042 inches. The upper curve represents the results from the polished specimens, while the lower curve, those of the specimens scratched by number 60 grit abrasive cloth. Only this one grade of abrasive was used on the 75S-T6. It was originally planned to also run curves for the other two abrasives. However, in view of the fact that the stress concentration factors determined were less than those reported by Bond¹⁵, it was felt that a rerun of the 24S material would be of greater value in forming a comparison of the

¹⁴Duchacek, op. cit., p. 20.

¹⁵Bond, op. cit., p. 30.

two materials.

24S-T3: A comparison of two investigations on 24S-T3 is shown in Figure 18. The S-N curves for 24S-T3 of thickness 0.0395 inches are shown in Figure 20. Once again the upper curve is for the polished specimens while the lower curve is for those scratched by the number 60 grit abrasive.

Figure 19 shows a direct comparison of the materials 24S-T3 and 75S-T6, both in the polished state. It can be seen that beyond approximately five-hundred-thousand cycles, the 75S-T6 has the higher fatigue strength, while at the lower number of cycles the 24S-T3 seems to possess the higher fatigue strength. For the data shown here, this difference at the lower number of cycles can only be given as a trend, since the tests were not extended beyond a stress setting of 45,000 pounds per square inch for the outside fiber. However, a confirmation of this trend is reported by G. H. Found¹⁶.

It should be noted that for a loading to failure in one-half cycle, the ultimate strength of the material is involved, and since the 75S-T6 has the larger ultimate strength, it is necessary for the S-N curves of the two

¹⁶Found, G. H., "The Notch Sensitivity in Fatigue Loading of Some Magnesium Base and Aluminum Base Alloys" A.S.T.M. Proceedings, Vol. 46, 1946, p. 796.

materials to cross at least twice, in the complete range of cycles from one-half cycle to, say five-hundred-million cycles. This of course, would mean that neither material is superior to the other in flexure fatigue strength at all numbers of cycles. This cannot be shown here, however, since no S-N curve covering the complete range of cycles from one-half to five-hundred-million is available for the two materials.

Shape Effect: For fatigue tests of sheet material, the values determined are usually less than those found for the same material using specimens of a different shape. Tests of the high strength aluminum alloy X76S-T indicate a 30 per cent reduction in endurance strength for rectangular specimens, as compared with round specimens run on the same vibratory type machine.¹⁷ An even greater reduction was found for square specimens. This same effect has been reported by others¹⁸. The surface hardening effect due to rolling and straightening of sheet material would tend to give it a higher endurance strength. While the depth affected by "cold

¹⁷Dolan, Thomas J. "Effects of Range of Stress and of Special Notches on Fatigue Properties of Aluminum Alloys Suitable for Airplane Propellers", N.A.C.A. Technical Note No. 852, pp. 1-20.

¹⁸Moore, H.F. "Report of the Research Committee on Fatigue of Metals" A.S.T.M. Proceedings, 41:133, 1941.

working" of this nature is small, it becomes a sizeable factor when compared to a sheet thickness of several hundredths of an inch. The same depth of strengthened material on a thickness of several inches would be negligible. This fact has been used to improve the fatigue life of parts by "shot peening."¹⁹

The sharp edge of the specimen, however, provides an effective stress raiser, which is more than enough to overcome any strengthening due to surface hardening, and accounts for the lower values of endurance strength.

Stress Concentration Factors: A stress concentration factor may be defined as the ratio of the endurance strength of the material to the endurance strength of the specimen with the stress raiser, at the same number of cycles.²⁰ For this report, the transverse scratches caused by the various abrasive cloths act as the stress raisers. The actual values of the stress concentration factors are recorded in tables III and IV. These were determined by dividing the ordinate of the curve for the polished specimens by the ordinate of

¹⁹Moore, H.F. "Strengthening Metals Parts by Shot Peening" Iron Age, Vol. 158, Nov. 28, 1946, p. 67 and Dec. 5, 1946, p. 81.

²⁰Seely, Fred B. Advanced Mechanics of Materials (New York: John Wiley and Sons, Inc., Eighth Printing, 1947), p. 202.

the curve for the scratched specimens. The ordinates were taken at the same number of cycles of stress application. This was done at a number of values of N , and these stress concentration factors averaged together to form one representative stress concentration factor for each abrasive. For the Alclad 75S-T6 scratched by crocus cloth, the factors are practically constant throughout the range of cycles. Those determined for the other two grits differ from the average by less than four per cent for the range of cycles covered. The factors determined for 75S-T6 and 24S-T3 vary slightly more. No explanation can be given for the fact that the Alclad 75S-T6 showed the greatest factors near the center of the cycle range, while the 75S-T6 and 24S-T3 showed the largest factors on both extremes of the range of cycles tested.

From tables III and IV, it is seen that for the Alclad 75S-T6 and 75S-T6, both scratched by number 60 grit cloth, the stress concentration factors are very nearly the same. The average factor for the Alclad 75S-T6 is 1.12, while for the 75S-T6 is 1.13. It should also be observed that the maximum and minimum factors are very nearly the same for the two materials, except that they occur at a different number of cycles as noted above. This would seem to indicate that Alclad

75S-T6 and 75S-T6 are almost equally sensitive in fatigue to a group of surface scratches. This same effect was found by Bond²¹ in his investigation on Alclad 24S-T3, and 24S-T3 with but one exception, and that was for the specimens scratched with grit number 60 abrasive. In this case the factor for the unclad material is much larger than that for the Alclad material. However, it is felt that this one particular value from the work of Bond is not in agreement with his other results for the following reason. Of the five abrasive grades used by Bond on the Alclad and bare material, for three, the factors determined for the Alclad and bare material were numerically the same to three figures, which are all that can be considered significant. For the fourth abrasive, the difference was less than two per cent, and yet for the fifth, grit number 60, the difference is greater than 10.5 per cent. In view of this, it is felt that the stress concentration factor determined by Bond for 24S-T3 scratched by grit number 60 abrasive is too large.

The average concentration factor determined for 24S-T3 scratched by number 60 abrasive cloth, from table IV, is 1.12. This is in close agreement with the 1.13 determined for 75S-T6 and 1.12 determined for Alclad

²¹Bond, loc. cit.

75S-T6, scratched by the same abrasive. It seems reasonable to conclude, at least as a first approximation, in view of the limited data, that 24S-T3 and 75S-T6, are almost equally notch sensitive to stress raisers such as those used in this investigation.

A further confirmation of almost equal notch sensitivity for 24S-T3 and Alclad 75S-T6 is found in a report for a single notch.²² The tests were made in bending and the thickness of the material was 0.064 inches. A single transverse surface notch on opposite sides of the specimen in the form of a sixty degree "V" with minimum radius of one-thousandth of an inch, and a depth of three-thousandths of an inch was used. At five hundred thousand cycles, the stress concentration factor for Alclad 75S-T6 was 1.31, and for 24S-T3 was 1.38. At ten million cycles, the stress concentration factor for Alclad 75S-T6 was 1.22, and was 1.18 for 24S-T3. From these results, it is noticed that the stress concentration factors vary with the number of cycles in a manner similar to that noted for Alclad 75S-T6 by this experimenter. It should also be observed that at the lower number of cycles, the Alclad 75S-T6 was the least notch sensitive while at the higher number of cycles, the 24S-T3 was the least notch

²²Found, op. cit., p. 715.

sensitive. The theoretical stress concentration factor is 2.0 for the above notch.

Since, for Alclad 75S-T6, the nominal thickness of the 72S cladding on each side is 4.0 per cent of the total thickness,²³ the depth of notch must have completely penetrated the clad surface. On the tests conducted for this report, the scratches in no case were through the clad surface, as can be seen from the table of depths.

A comparison of the stress concentration factors for scratched Alclad 75S-T6 with those available for scratched Alclad 24S-T3²⁴ shows a percentage difference of from 5 to 10 per cent with those for Alclad 75S-T6 as the lower of the two. A further comparison of the Alclad 24S-T3 values with those reported for a single notch, which has been shown to be the more damaging of the two cases,²⁵ might indicate the factors reported by Bond for the scratched Alclad 24S-T3 to be too large. Andrews²⁶ found for a transverse surface notch on each side of the sheet made by a

²³Anonymous, Alcoa Aluminum and Its Alloys (Pittsburgh, Penna: Aluminum Company of America, 1947), p. 102.

²⁴Bond, op. cit., p. 29.

²⁵Moore, R. R. "Effect of Grooves, Threads, and Corrosion Upon the Fatigue of Metals", A.S.T.M. Proceedings, Vol. 26, Part II, 1926, p. 255.

²⁶Andrews, H. J. and Stickley, G.W. "Effect of Scratches on Fatigue Strength of Alclad Sheet", Aviation June 1943, p. 145.

tool with a sixty degree "V", and a minimum radius of less than one ten-thousandth of an inch, with depth equal to 85 per cent of the alclad thickness, an average stress concentration factor of 1.11 for Alclad 24S-T3. For a notch depth of 55 per cent of the alclad thickness, a factor of 1.06 is reported.

One factor which has not been directly evaluated is the effect of the scratch or notch at the edge of the specimen. Since a great majority of the fractures began at one edge of the specimen and progressed across, it was felt that the scratch depth was not the most important factor in the determination of the failure. In Figure 9, it can be seen that there were many stress raisers along the edge of the specimens which did not extend across the surface as scratches. The intersection of these, with the minute longitudinal scratches which remained from the edge polishing operation, could very well have been the deciding factor for failure, and more important than the depth of scratch on the surface of the specimen. The difference in edge surface finish might also account for the lower values of stress concentration factors found for Alclad 75S-T6 and 75S-T6. As was noted under preparation of the specimens, the edge was considered to be better polished than those specimens used in previous tests.

One other difference can be mentioned to account for the higher stress concentration factors reported by Bond.²⁷ The curve for polished 24S-T3 specimens, which was used to determine the stress concentration factors, consistently runs from 3,000 to 4,000 pounds per square inch higher, for the same number of cycles, than either the similar curve of Duchacek²⁸ or of the present investigation. Figure 18 shows the S-N curve determined by Duchacek with the experimental points found by the present author superimposed to demonstrate the extent of similarity of the two curves. No reason can be found for this difference, since all work was done using the same machine and similar specimens. It is possible however, that the first specimens were slightly oversize, since they were not made on the router as were those of Duchacek and the author. This last statement can only be considered as a supposition to explain the difference as there is no factual evidence to prove they were either undersize or oversize.

APPLICATION TO DESIGN

It should be pointed out that not only the low stress (high number of cycles) end of the S-N curve, but the whole curve is important in design work. There

²⁷Bond, loc. cit.

²⁸Duchacek, op. cit., p. 34.

are component parts in aircraft structures where the number of stress alternations in the lifetime of the aircraft may be estimated quite closely. One such example is the cycle of stress caused by pressurizing and depressurizing the cabin of modern transport and military aircraft. As the art of aircraft design and analysis progresses, the number of component parts whose stress histories can be approximated, will be greatly increased. In instances such as these, a much higher working stress can be used with no danger of fatigue failure, since an infinite life is not required. It is therefore, also important to know the effect of stress raisers on the material through a wide range of cycles.

In general, the stress concentration factors as determined by using laboratory test specimens, are not directly applicable to the design or analysis of larger parts. One reason is that with models, the work hardening effect at, and near, the surface is in greater proportion than in full-sized objects. This tends to give lower stress concentration factors than would be experienced in the full-sized part. However, the factors determined in this report could in all probability be applied with safety to a similarly loaded sheet with a similar surface roughness since here the thickness of the specimens is the same as that

for the sheets used in industry. The stress distribution on a cross-section should then be the same for specimen or for a sheet in actual use.

The stress concentration factors here determined, should not be directly applied to parts which are other than sheets of the same magnitude of thickness. For small stress raisers with high theoretical stress concentration factors, tests have shown that with small specimens, the actual stress concentration factor is less than that predicted by theory.^{29,30,31} However, it is believed that on larger specimens, the stress concentration factor would approach the theoretical value.^{32,33} Therefore, the values usually determined

²⁹Brueggeman, W.C. and Mayer, M. "Axial Fatigue Tests at Zero Mean Stress of 24S-T and 75S-T Aluminum Alloy Strips With A Central Circular Hole", Technical Note No. 1611, N.A.C.A. August 1948.

³⁰Found, op. cit., p. 715.

³¹Peterson, R.E., "Model Testing as Applied to Strength of Materials" A.S.M.E. Transactions, 55:79, 1933.

³²Peterson, R.E. and Wahl, A.M. "Two and Three Dimensional Cases of Stress Concentration, and Comparison With Fatigue Tests", American Society of Mechanical Engineers, Journal of Applied Mechanics Vol. 3, No. 1, 1936, pA-15.

³³Timoshenko, S. "Stress Concentration and Fatigue Failures" Engineer May 9, 1947, p. 398 and May 16, 1947, p. 421.

on small scale tests have recently been subjected to suspicion.³⁴

Regardless of the numerical value of the stress concentration factors, the tests conducted here have a very definite use in comparing the two different aluminum alloys 75S and 24S under a similar surface condition.

³⁴Heywood, R.B., "The Relationship Between Fatigue and Stress Concentration", Aircraft Engineer, March 1947, p. 82.

CONCLUSIONS

As a result of the tests conducted and the previous discussion in the main body of this paper, the following conclusions seem warranted:

1. The materials Alclad 75S-T6 sheet and 75S-T6 sheet are almost equally notch sensitive in flexure fatigue to small transverse scratches.
2. The materials 75S-T6 sheet and 24S-T3 sheet have very nearly the same notch sensitivity to small transverse scratches when tested in flexure fatigue.
3. Stress concentration factors for Alclad 75S-T6 increase with an increase in depth of scratch.
4. Stress concentration factors for Alclad 75S-T6 and Alclad 24S-T3 are of the same magnitude for similar surface scratches.
5. Neither 75S-T6 or 24S-T3 is superior to the other for the complete range of stress cycles, but 75S-T6 sheet possesses the higher endurance strength in the range of cycles above one million.
6. Airplane parts subjected to repeated loads, or steady loads with repeating loads superimposed, should be designed on a basis of fatigue strength, rather than ultimate strength.

7. It is suggested that a series of flexure fatigue tests be conducted on sheet 75S and 24S material with a single stress raiser of a certain known theoretical stress concentration factor, with the stress raiser not extending to the edges of the specimen.

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APPENDIX I
Historical Note

HISTORICAL NOTE

For many years the subject of fatigue, or progressive failure, in metals has been under study, and each passing year has shown it to be of increasing importance.

In the middle of the nineteenth century when wrought iron was beginning to replace stone and brickwork as a major building material, it was suggested by some, that since the principles of design were not too well understood, experiments should be carried out.³⁵

It was only then discovered that a repeated load could cause failure, and that the failure was due to the repeated load rather than due to any reduction of the ultimate static strength of the material with age.

Experiments on built-up wrought iron girders were carried out in England in 1864 by Fairbrain.³⁶ He determined that in the case of completely reversed stress, that is, from a tensile to an equal compressive value, the maximum stress should not be greater than one-third the ultimate static strength.

The really outstanding pioneer, in the study of fatigue was Herr A. Wohler, Chief Locomotive Super-

³⁵Gough, H.J., The Fatigue of Metals (London: Ernest Benn Limited, 1926), p. 4.

³⁶Marin, J., Mechanical Properties of Materials and Design (New York: McGraw-Hill Book Co., Inc., 1942), p. 117.

intendent of the Royal Lower Silesian Railway, who in 1862 undertook to determine the cause of failure of axles on railway cars and locomotives. His extensive series of tests continued for over ten years and covered the various methods of repeated loading with several different specimen shapes.³⁷ In one group of tests, the topic of stress concentration in fatigue work was approached. A specimen shape with a rapid change of section was tested both with and without fillets. The specimen with the fillets withstood twelve times the number of load applications as the one without the fillet.

This was, in effect an experimental determination of a stress concentration factor for that particular fillet.

Since the time of Wohler, much work has been done to establish the endurance strengths of various materials and some studies made on the effect of certain stress raisers on the endurance strength.

The nature of fatigue has not yet passed the phenomena stage³⁸ in spite of the work which has been done.

³⁷An account in English of Wohler's work can be found under "Wohler's Experiments on the Fatigue of Metals", Engineering (London, March 1871), 11:199.

³⁸Jackson, L.R. and others, "An Evaluation of the Fatigue Phenomena in Aircraft" (New York: A Sherman M. Fairchild Publication Fund Paper by the Institute of Aeronautical Sciences, July 1946), p. 30.

APPENDIX II, Tables

TABLE I

MECHANICAL PROPERTIES OF THE ALUMINUM ALLOYS USED IN FATIGUE TESTS

Material	Ultimate Tensile Strength, Kips Per Square Inch	Yield Strength (0.2% Off set), Kips Per Square Inch	Modulus of Elasticity, Kips Per Square Inch	Per Cent Elongation in 2 Inches
Alclad 75S-T6	74.2	65.5	10,000	10.4
75S-T6	81.2	72.5	10,200	9.9
24S-T3	69.2	52.8	9,800	16.4

TABLE II
MAXIMUM DEPTH OF SCRATCHES

Material	Abrasive	Depth of Scratch in Inches
Alclad 75S-T6	Crocus Cloth	0.00015
Alclad 75S-T6	Grit No. 100	0.00042
Alclad 75S-T6	Grit No. 60	0.00055
75S-T6	Grit No. 60	0.00027
24S-T3	Grit No. 60	0.00030

TABLE III

VALUES OF FLEXURE FATIGUE STRENGTH AND STRESS CONCENTRATION
FACTORS FOR ALCLAD 75S-T6 WITH VARIOUS SURFACE CONDITIONS

Cycles	Polished		Crocus Cloth		100 Grit		60 Grit	
	Stress*	Factor	Stress*	Factor	Stress*	Factor	Stress*	Factor
10^4	45.4	1.00	44.3	1.02	43.5	1.04	41.3	1.10
5×10^4	29.6	1.00	28.7	1.03	28.2	1.05	26.5	1.12
10^5	24.2	1.00	23.4	1.03	22.8	1.06	21.4	1.13
5×10^5	15.9	1.00	15.4	1.03	14.5	1.10	13.8	1.15
10^6	14.4	1.00	14.0	1.03	13.0	1.11	12.4	1.16
5×10^6	12.4	1.00	12.2	1.02	11.7	1.06	11.2	1.11
10^7	11.8	1.00	11.6	1.02	11.5	1.03	10.9	1.08
Average Stress Concentration Factor		1.00		1.03		1.06		1.12

*Note: Values of stress are given in kips per square inch.

TABLE IV

VALUES OF FLEXURE FATIGUE STRENGTH AND STRESS CONCENTRATION
FACTORS FOR 75S-T6 AND 24S-T3 FOR VARIOUS SURFACE CONDITIONS

75S-T6				24S-T3			
	Polished	60 Grit			Polished	60 Grit	
Cycles	Stress*	Stress*	Factor	Cycles	Stress*	Stress*	Factor
2×10^4	47.5	40.7	1.17	2×10^4	48.3	40.4	1.19
5×10^4	39.0	35.5	1.10	5×10^4	39.3	35.0	1.12
10^5	33.7	31.2	1.08	10^5	33.5	31.1	1.08
5×10^5	25.5	23.2	1.10	5×10^5	25.6	23.5	1.09
10^6	24.3	21.3	1.14	10^6	23.7	21.3	1.12
5×10^6	23.2	19.6	1.13	5×10^6	21.4	19.0	1.13
10^7	23.0	19.3	1.19	10^7	21.0	18.8	1.12
Average Stress Concentration Factor			1.13	Average Stress Concentration Factor			1.12

*Note: Values of stress are given in kips per square inch.

APPENDIX III, Figures

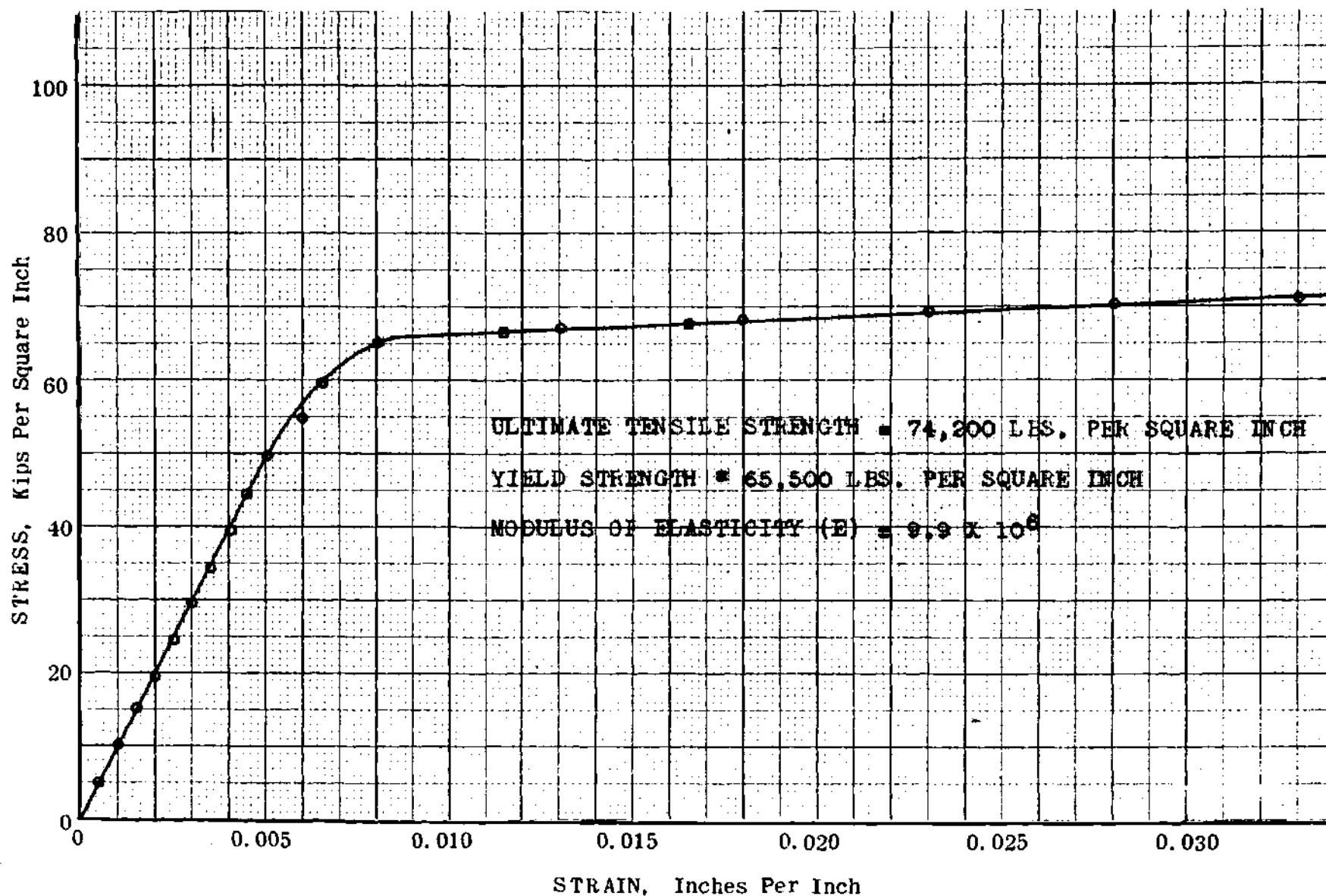


FIGURE 1. TENSILE STRESS-STRAIN CURVE FOR 0.039 INCH ALCLAD 75S-T6 ALUMINUM ALLOY SHEET

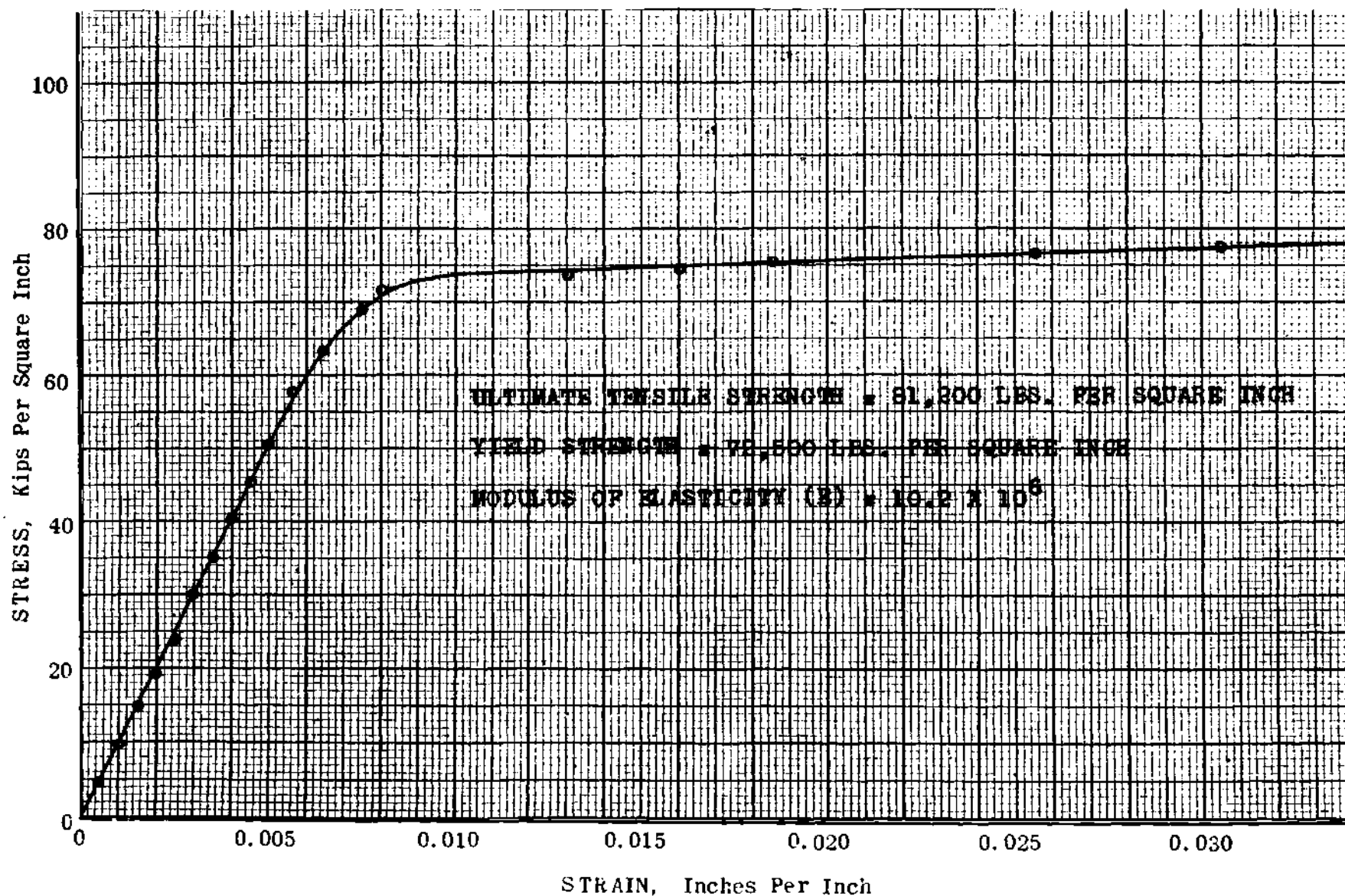


FIGURE 2. TENSILE STRESS-STRAIN CURVE FOR 0.042 INCH 75S-T6 ALUMINUM ALLOY SHEET

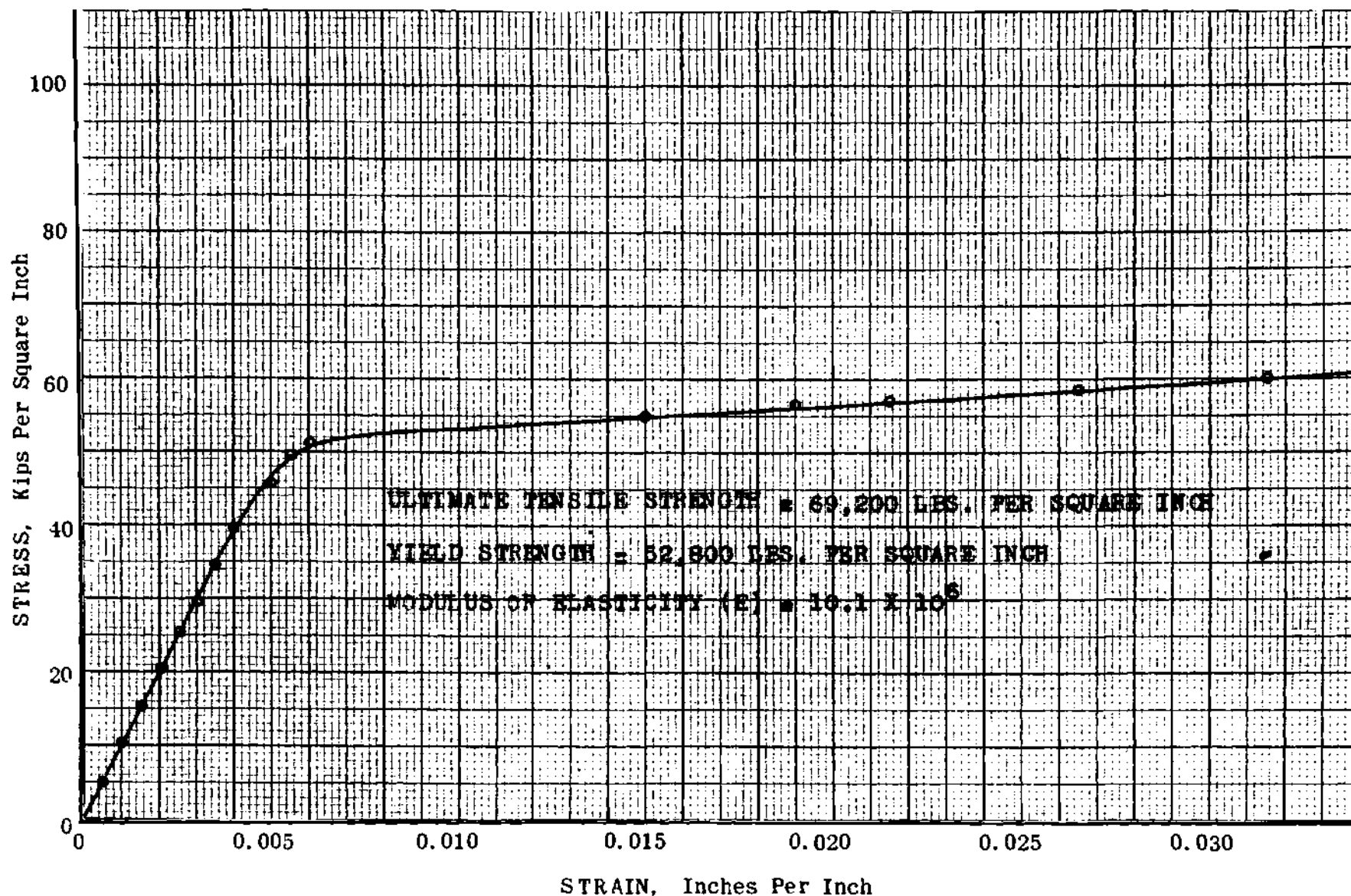


FIGURE 3. TENSILE STRESS-STRAIN CURVE FOR 0.0395 INCH 24S-T3
ALUMINUM ALLOY SHEET

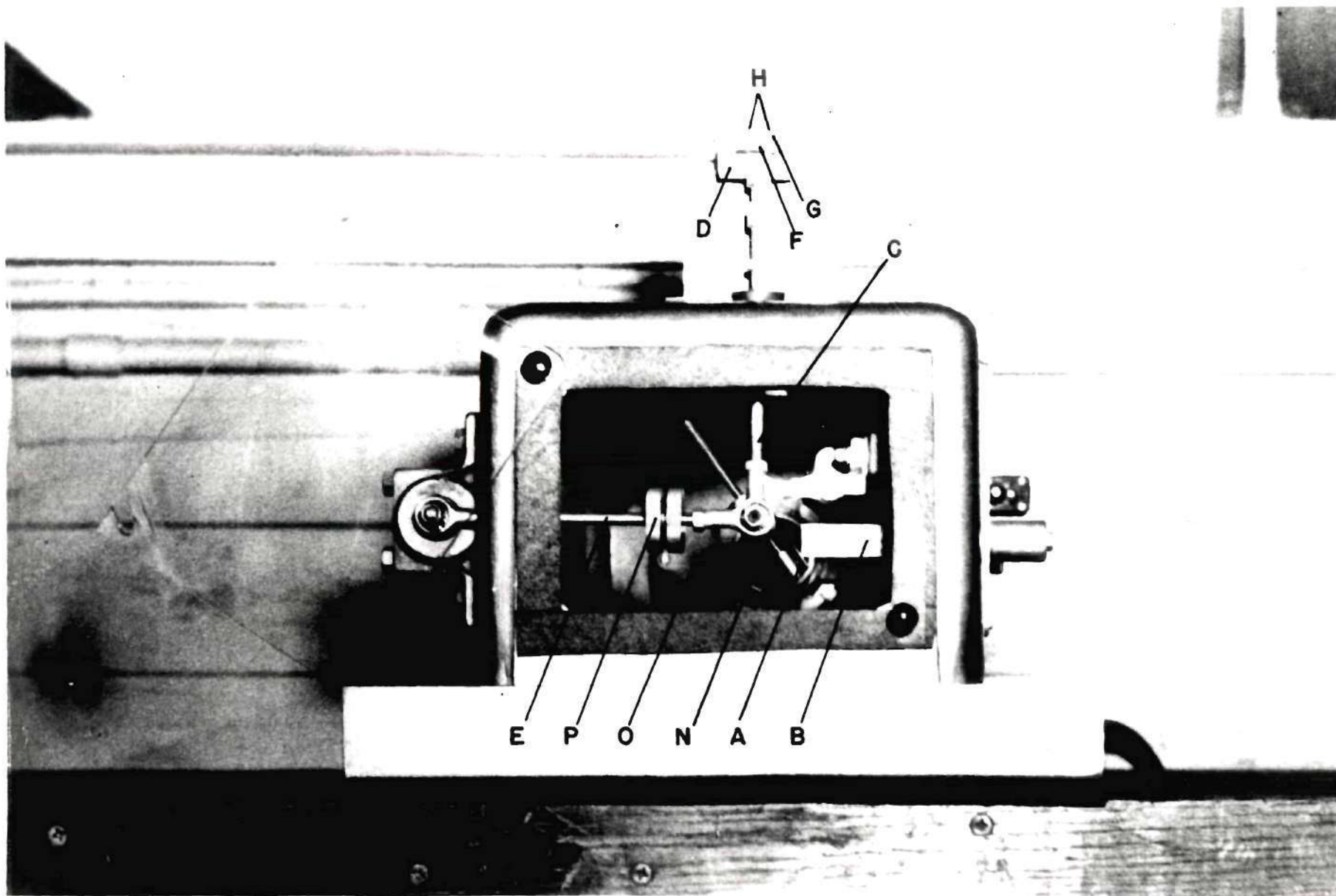


FIGURE 4. SONNTAG FLEXURE FATIGUE MACHINE MODEL SF-2

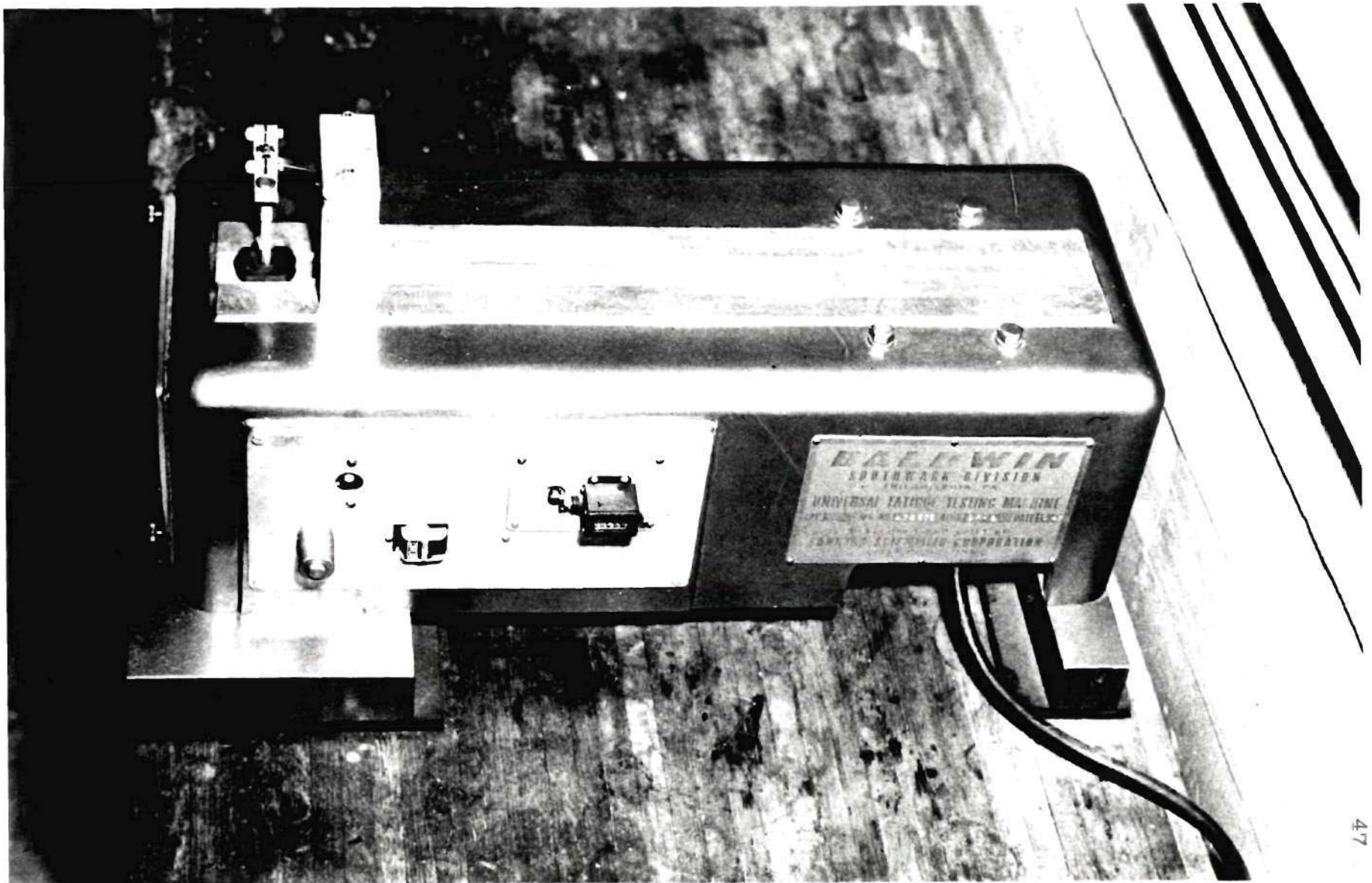


FIGURE 5. SONNTAG FLEXURE FATIGUE MACHINE MODEL SF-2

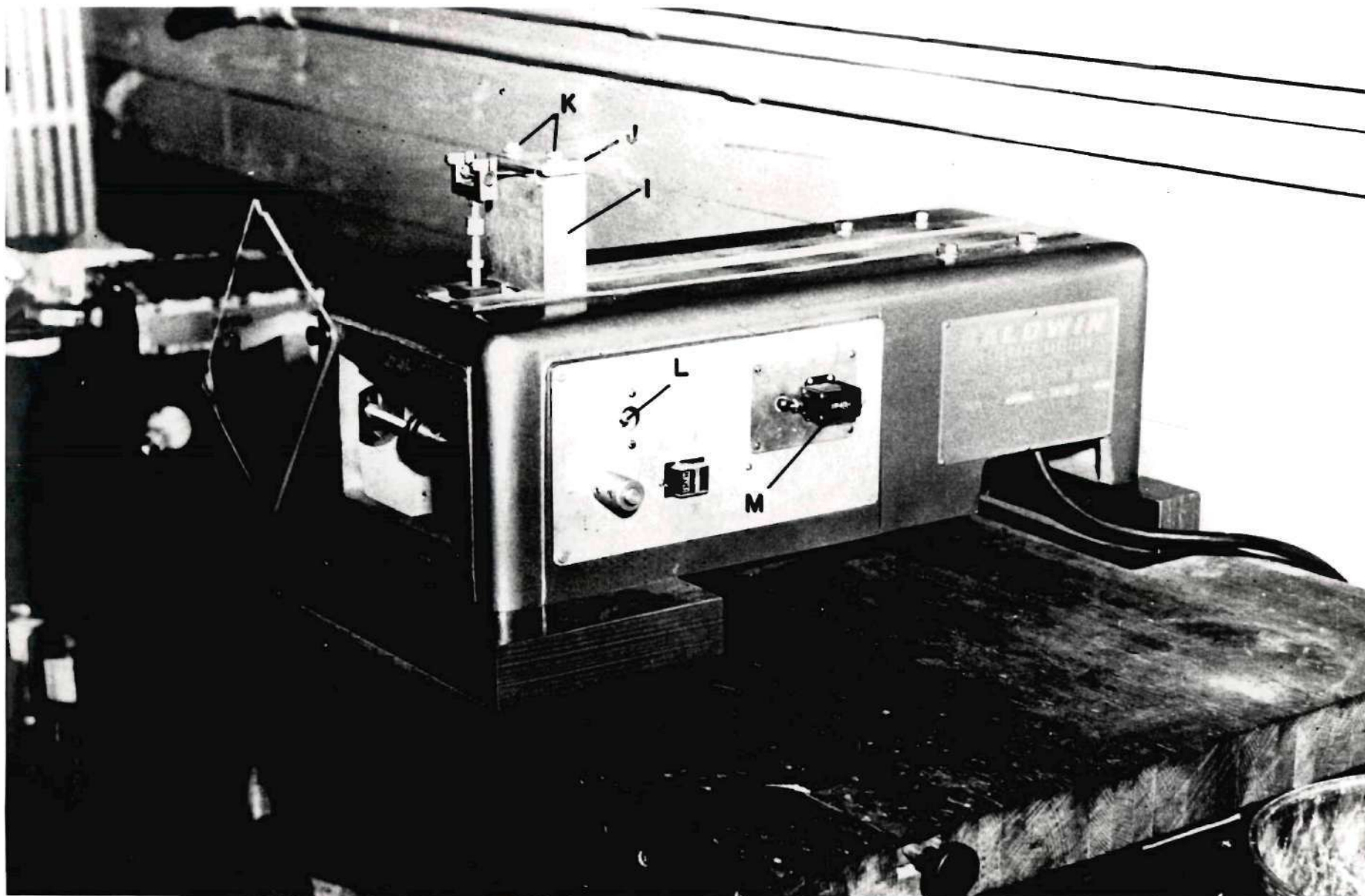
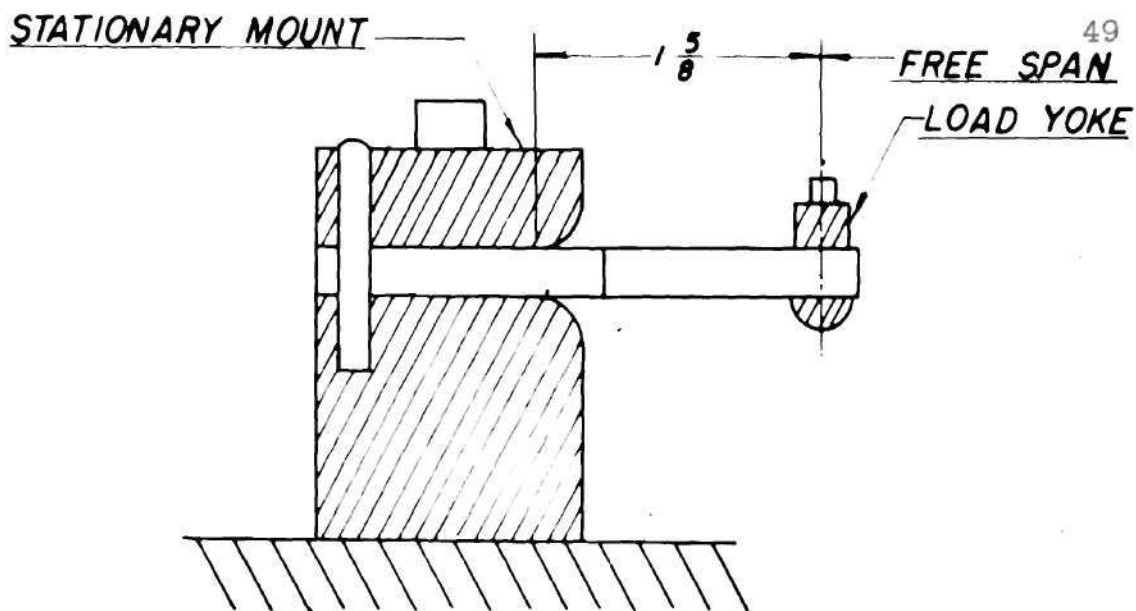
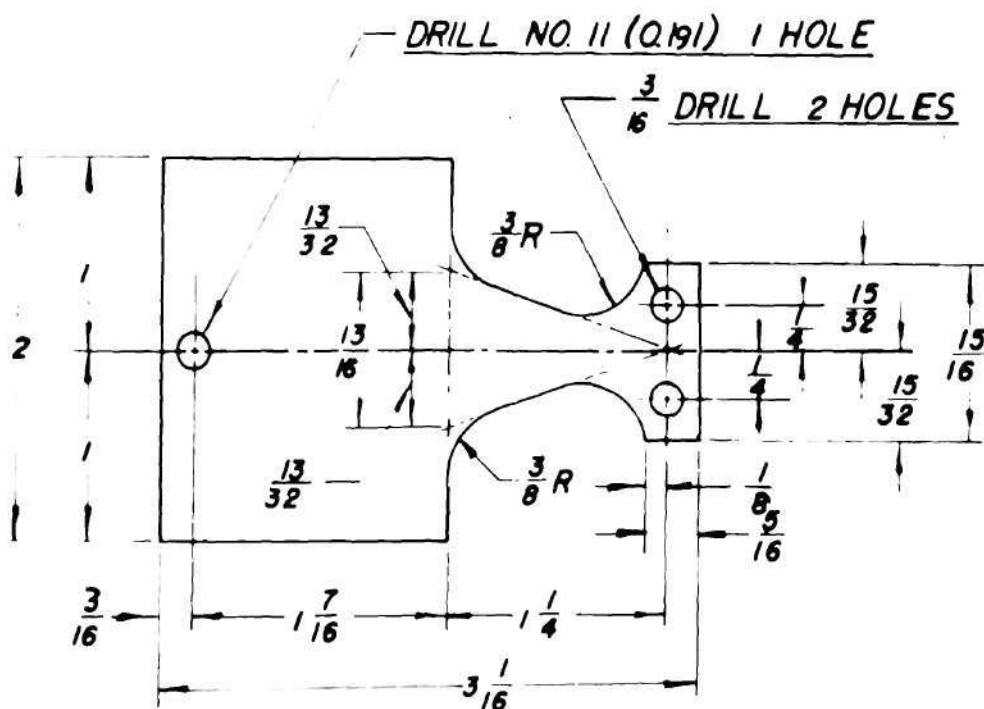


FIGURE 6. SONNAT FLEXURE FATIGUE MACHINE MODEL SF-2



CROSS SECTIONAL VIEW OF
SPECIMEN MOUNTING



SPECIMEN DETAILS

ALL DIMENSIONS IN INCHES

FIGURE 7. SPECIMEN AND MOUNTING DETAILS

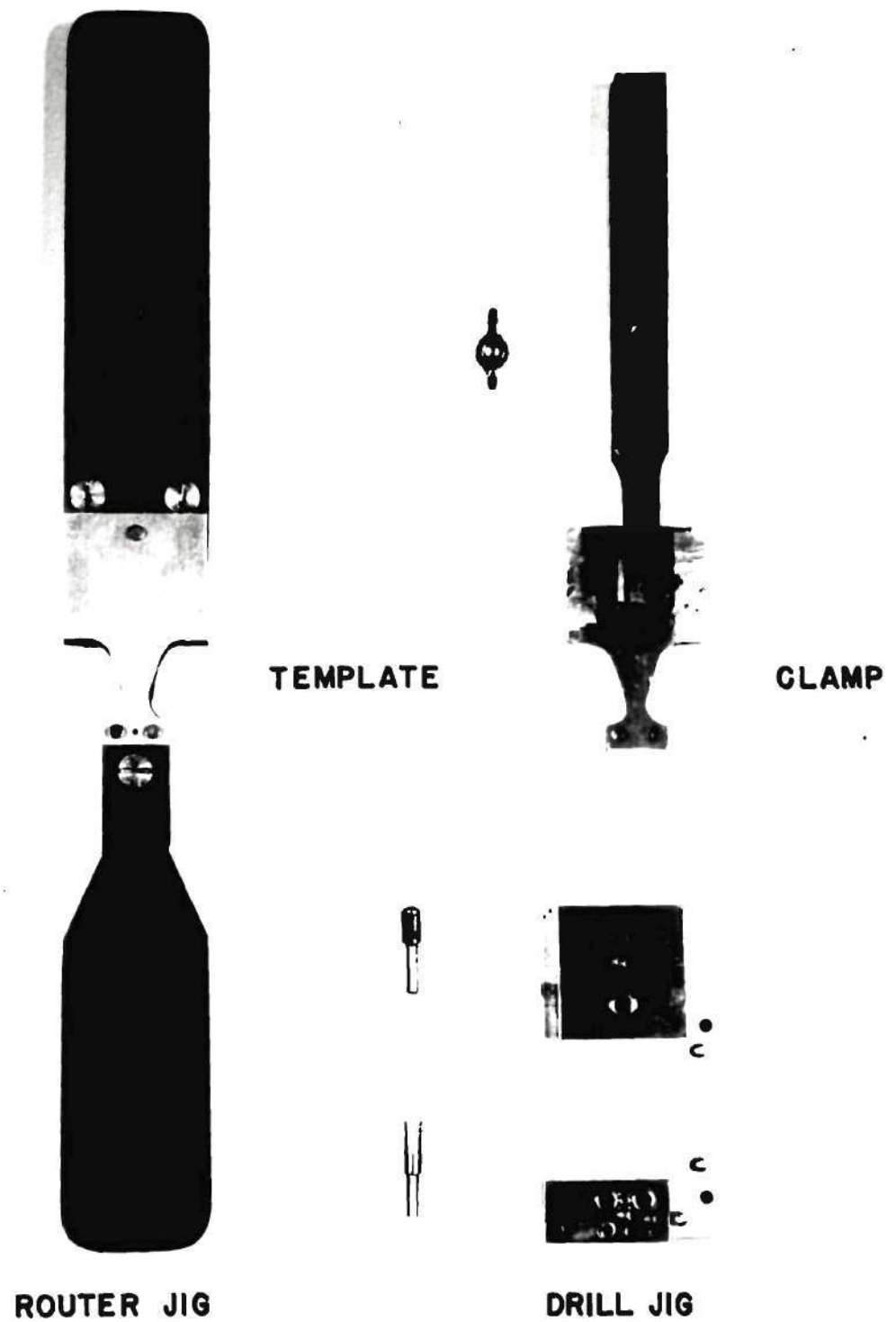


FIGURE 8. PHOTOGRAPH OF DRILL JIG AND ROUTER JIG

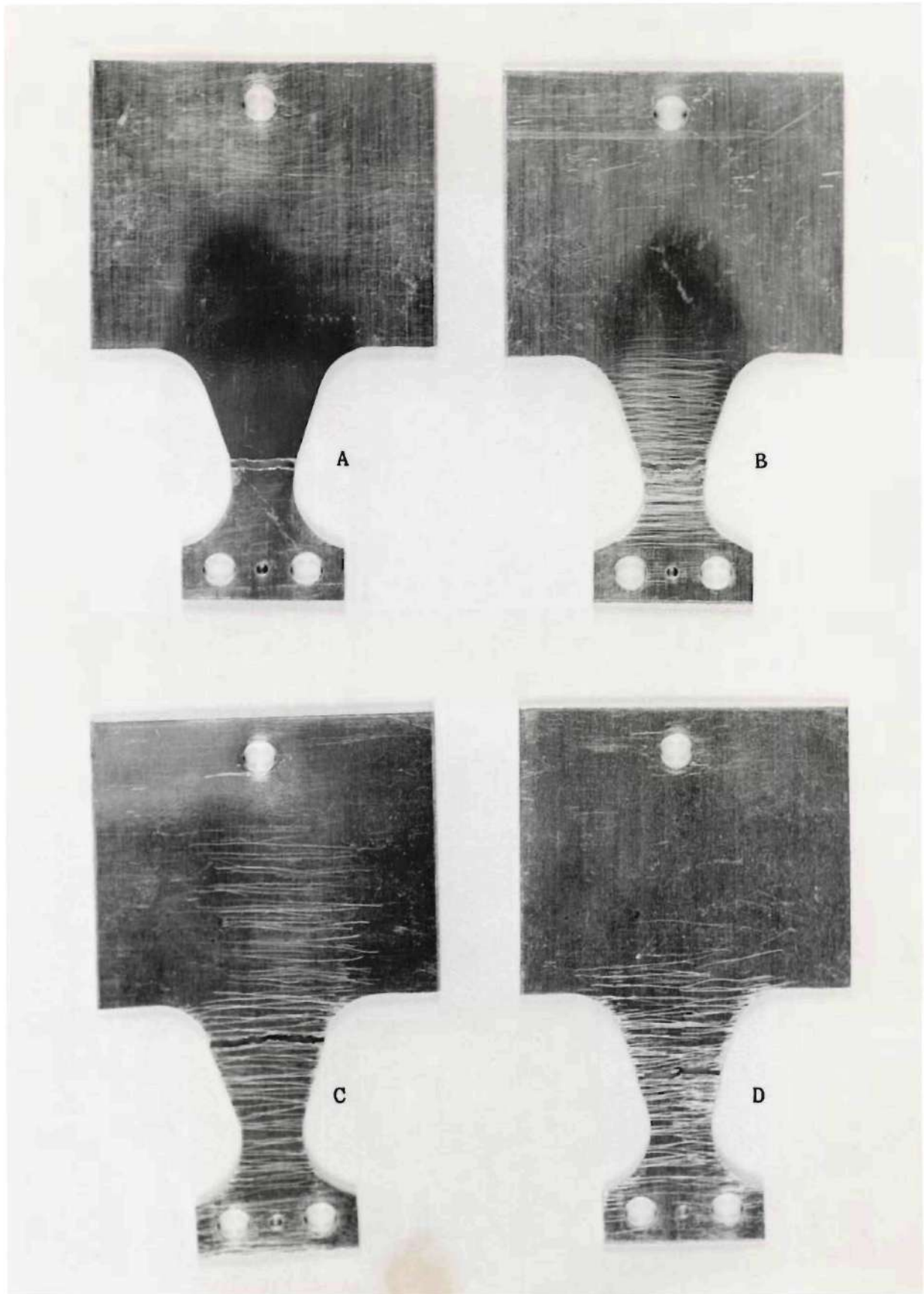


FIGURE 9. FRACTURED ALCLAD 75S-T6 SPECIMENS, SURFACE FINISH:
A. POLISHED, B. CROCUS CLOTH, C. GRIT NO. 100, D. GRIT NO. 60.

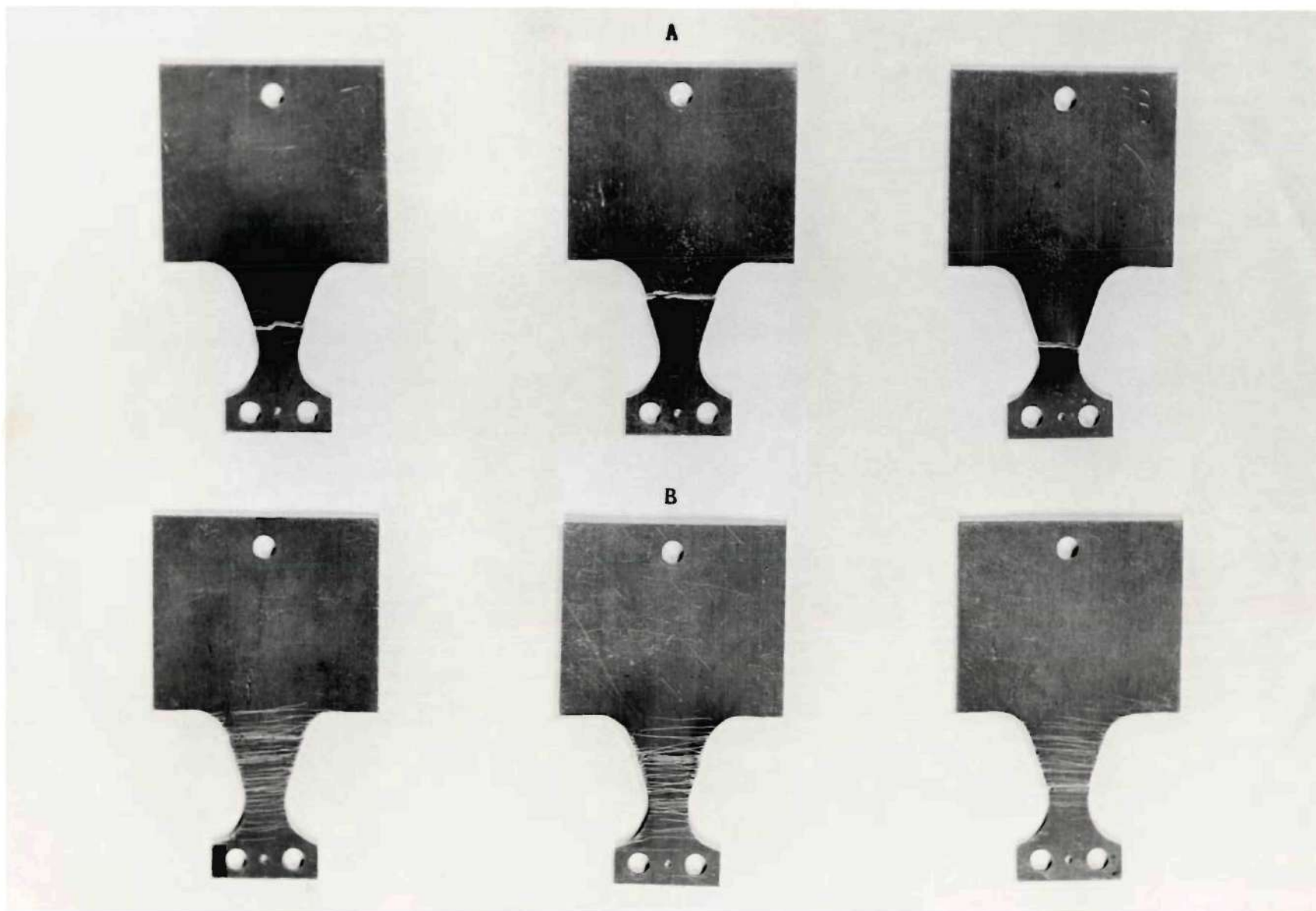


FIGURE 10. FRACTURED 75S-T6 SPECIMENS SURFACE FINISH: A. POLISHED B. GRIT NO. 60

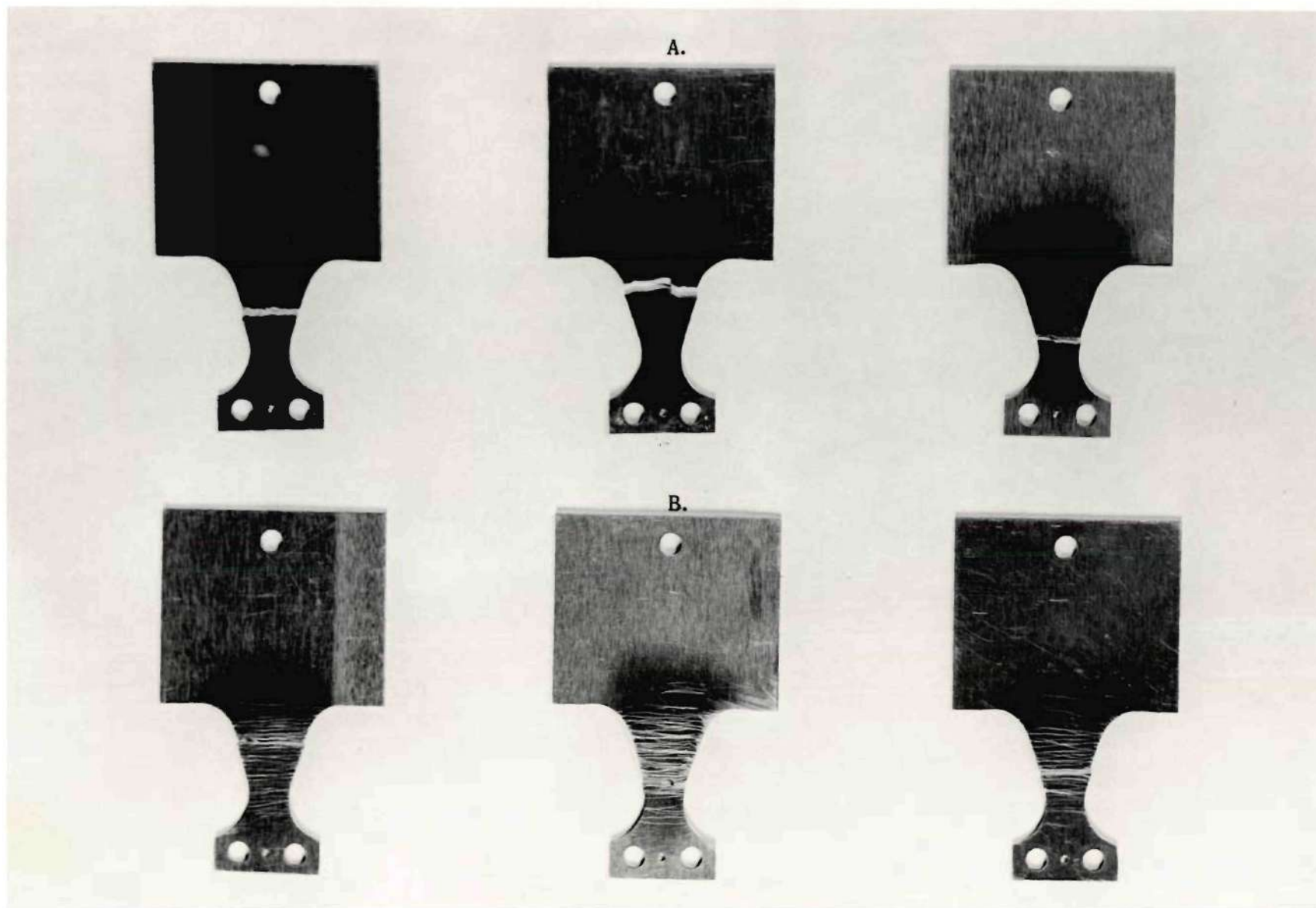


FIGURE 11. FRACTURED 24S-T3 SPECIMENS. SURFACE FINISH: A. POLISHED, B. GRIT NO. 60

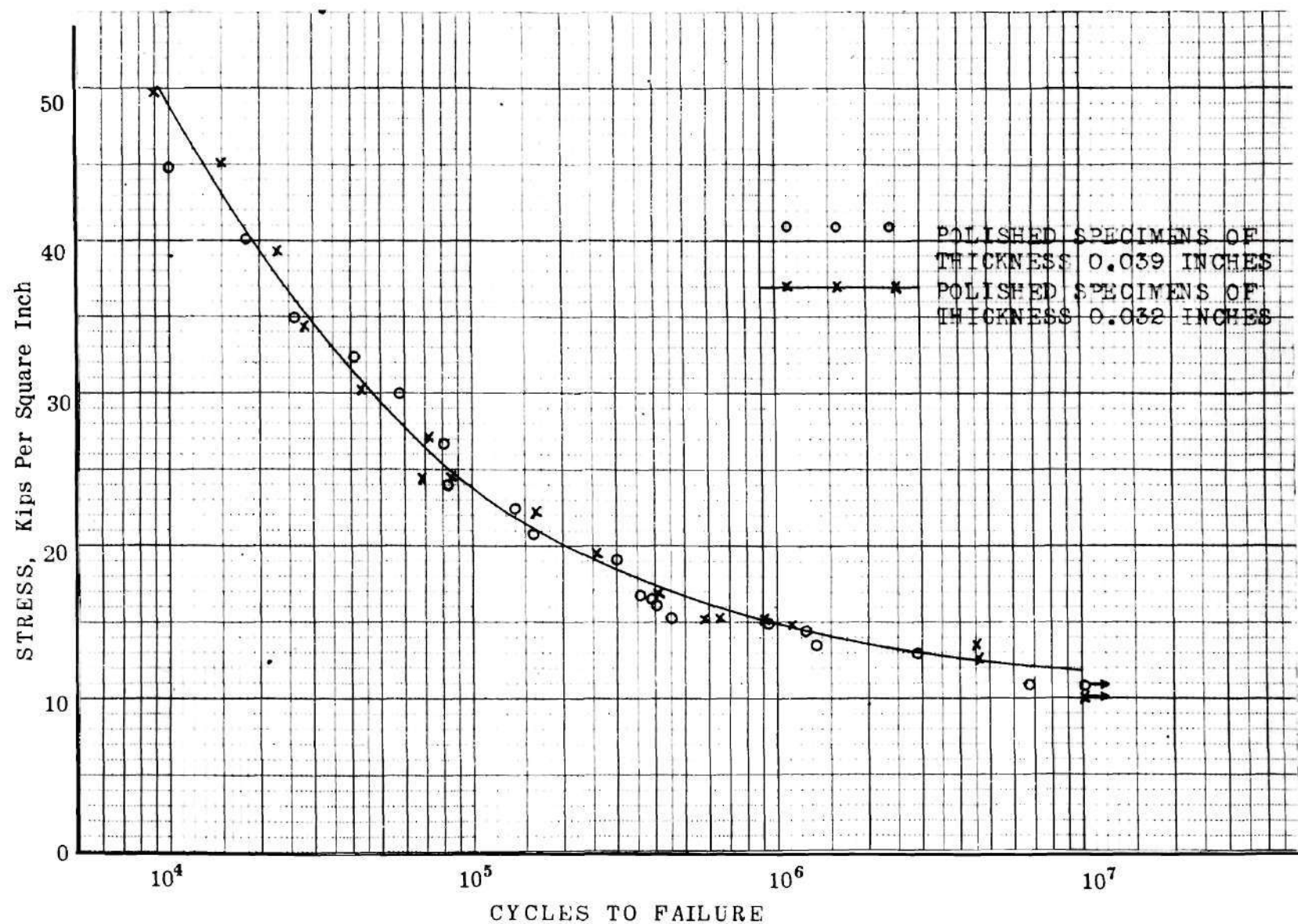


FIGURE 12. COMPARISON OF FATIGUE FLEXURE STRENGTHS FOR ALCLAD 75S-T6 SHEET OF THICKNESS 0.039 AND 0.032 INCHES

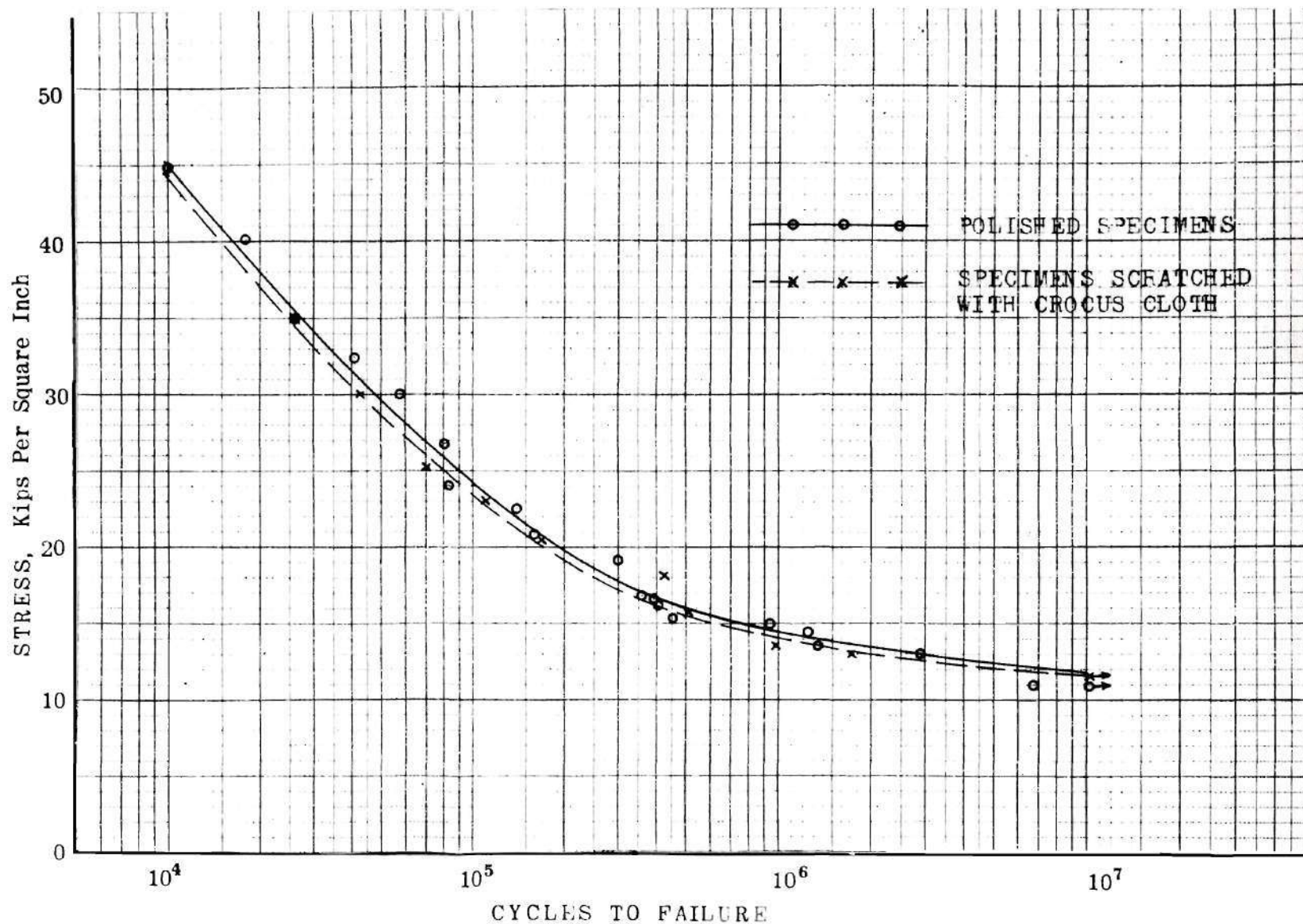


FIGURE 13. FLEXURE FATIGUE STRENGTH FOR 0.039 INCH ALCLAD 75S-T6 SHEET

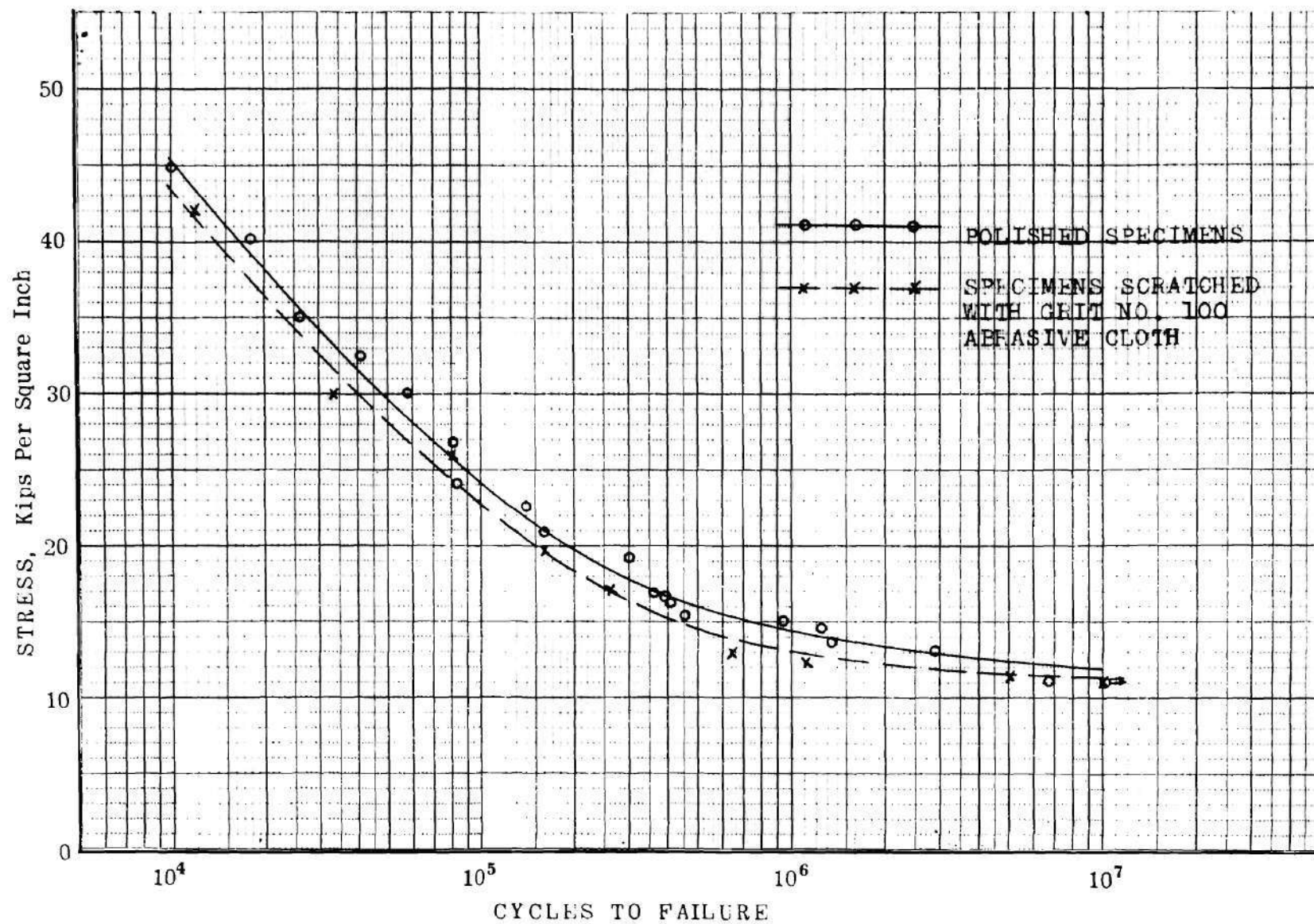


FIGURE 14. FLEXURE FATIGUE STRENGTH OF 0.039 INCH ALCLAD 75S-T6 SHEET

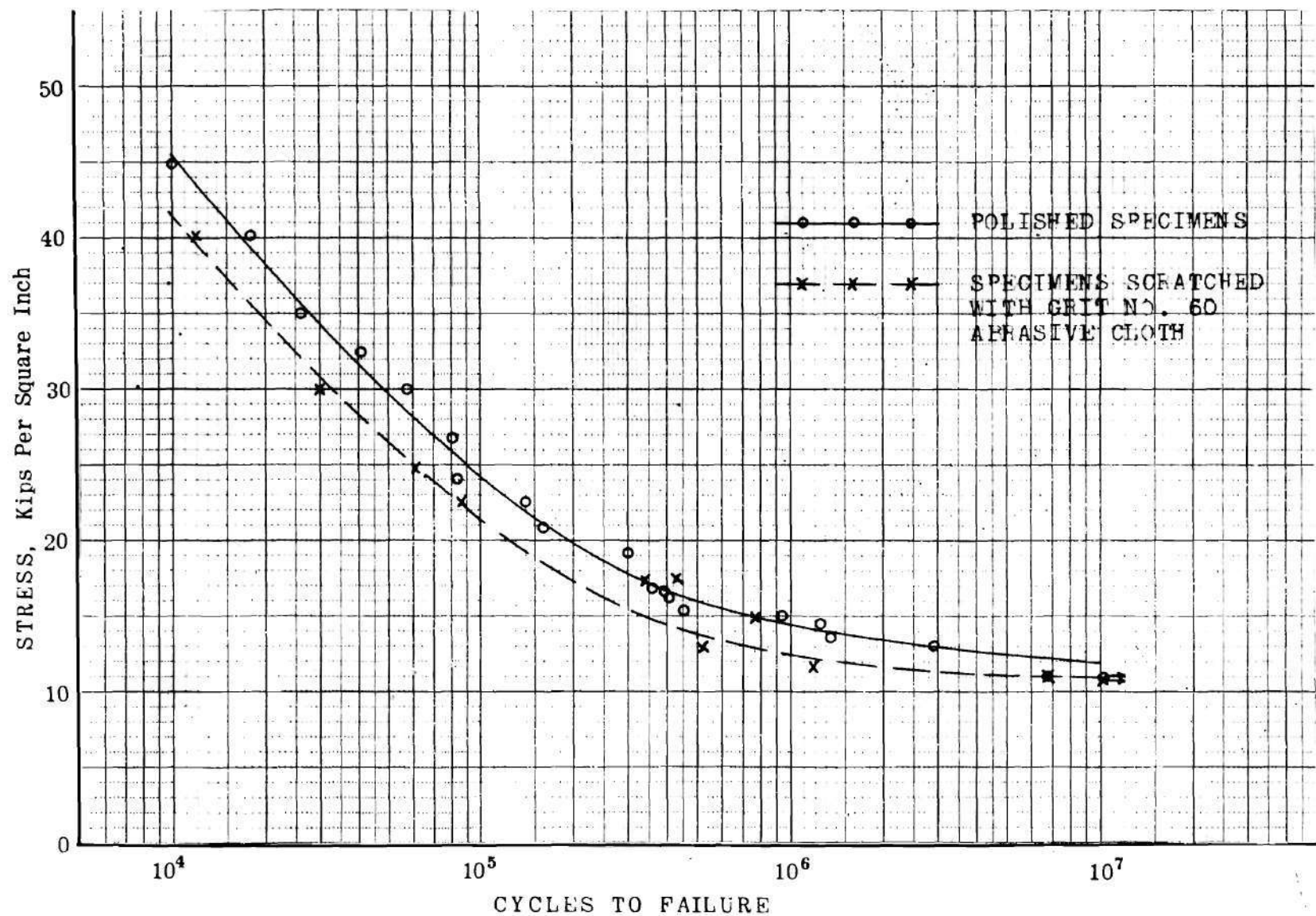


FIGURE 15. FLEXURE FATIGUE STRENGTH OF 0.039 INCH ALCLAD 75S-T6 SHEET

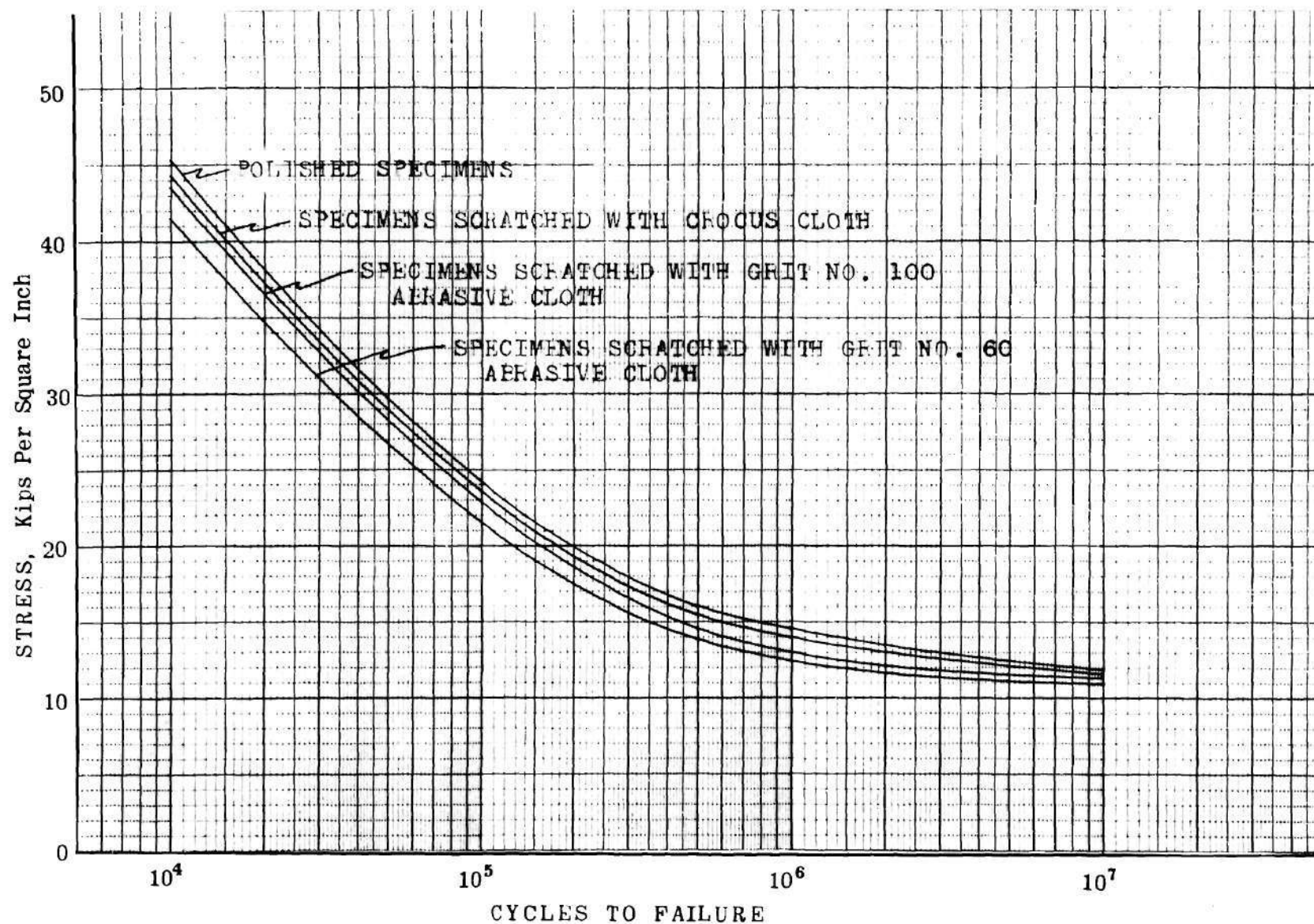


FIGURE 16. COMPARISON OF FLEXURE FATIGUE STRENGTHS FOR 0.039 INCH ALCLAD 75S-T6 SHEET SCRATCHED WITH VARIOUS ABRASIVES

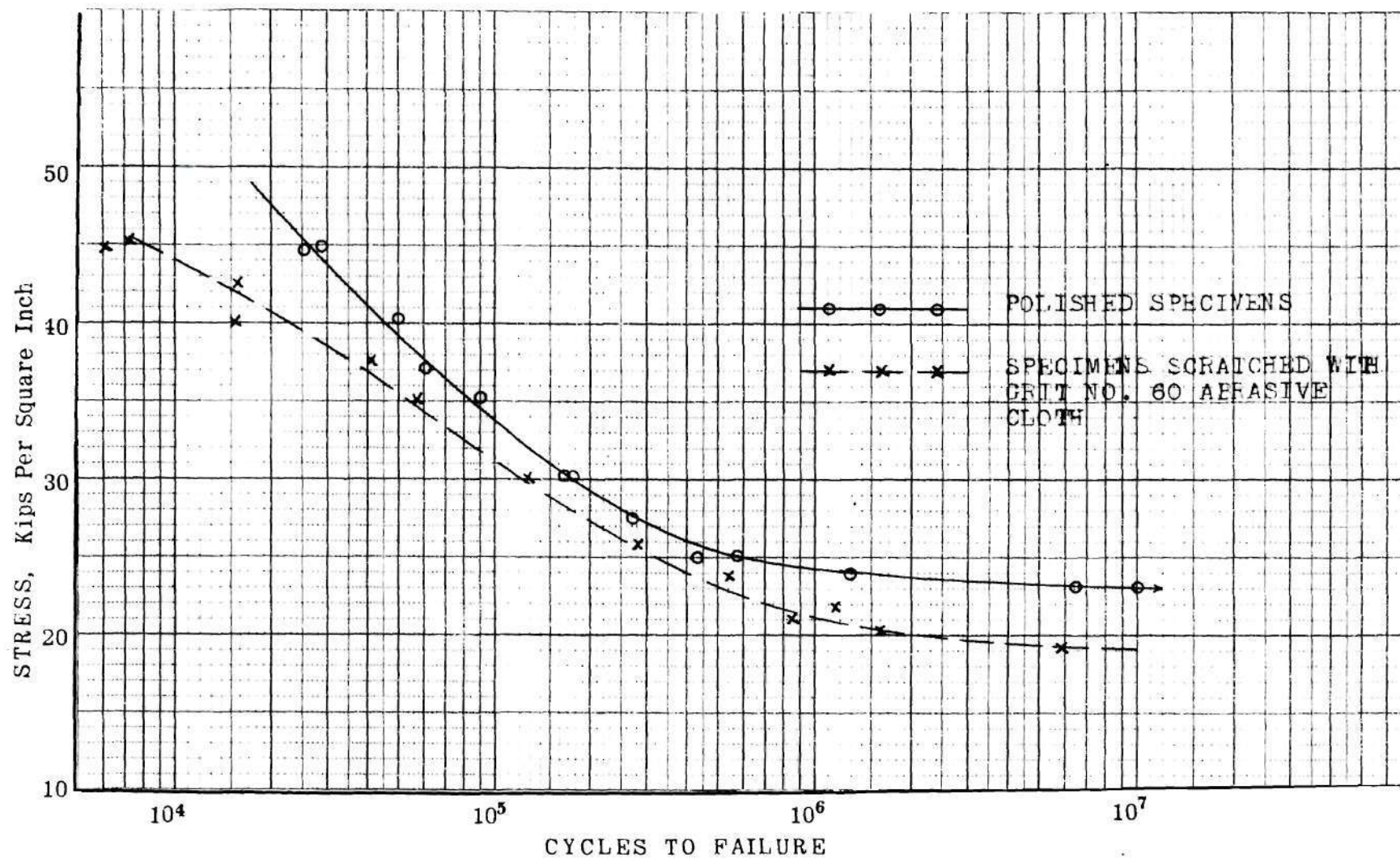


FIGURE 17. FLEXURE FATIGUE STRENGTH OF 0.042 INCH 75S-T6 SHEET

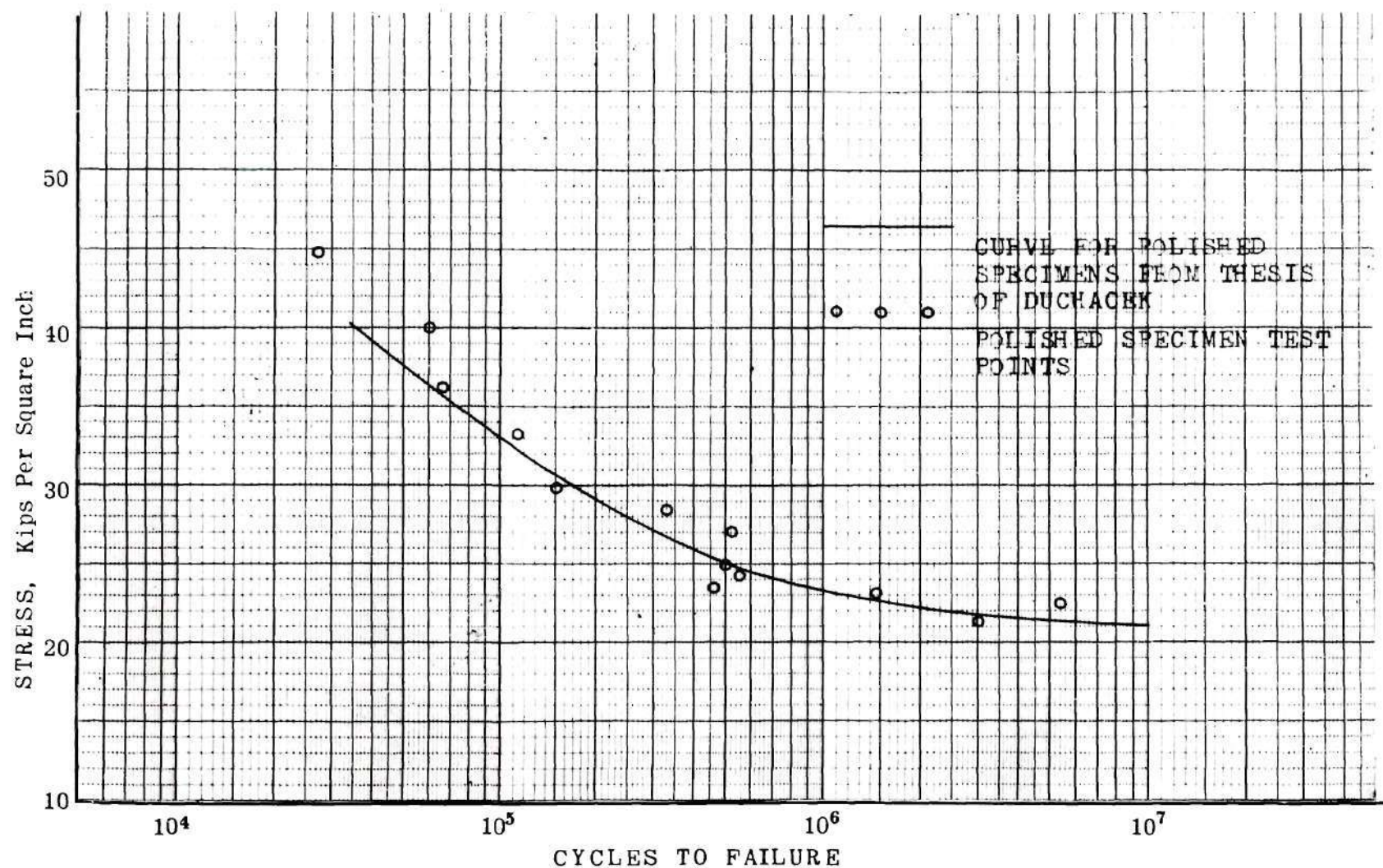


FIGURE 18. COMPARISON OF TEST RESULTS FOR TWO INVESTIGATIONS IN FLEXURE FATIGUE ON 24S-T3 SHEET

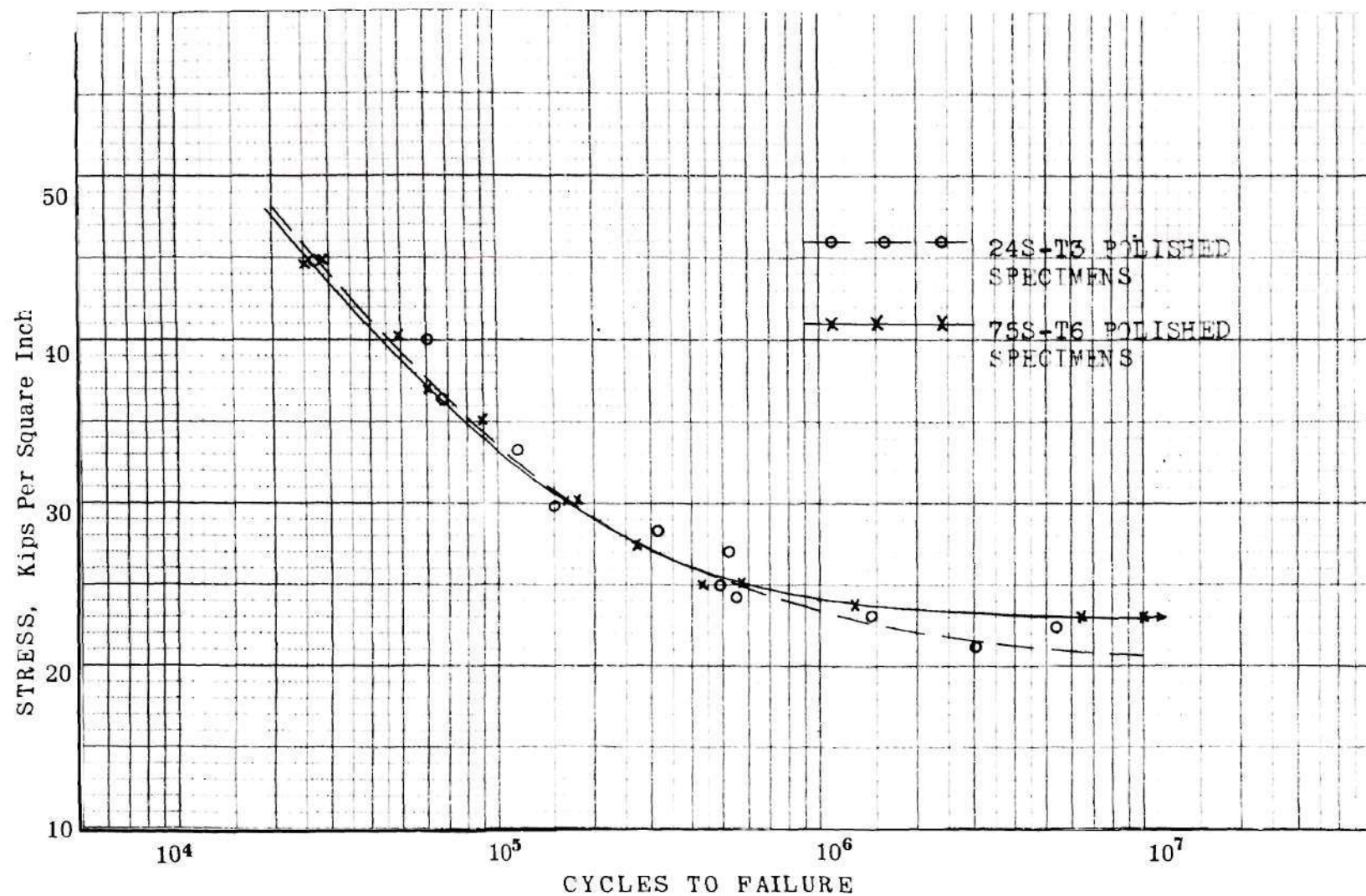


FIGURE 19. COMPARISON OF FLEXURE FATIGUE STRENGTHS FOR SHEET 24S-T3 AND 75S-T6

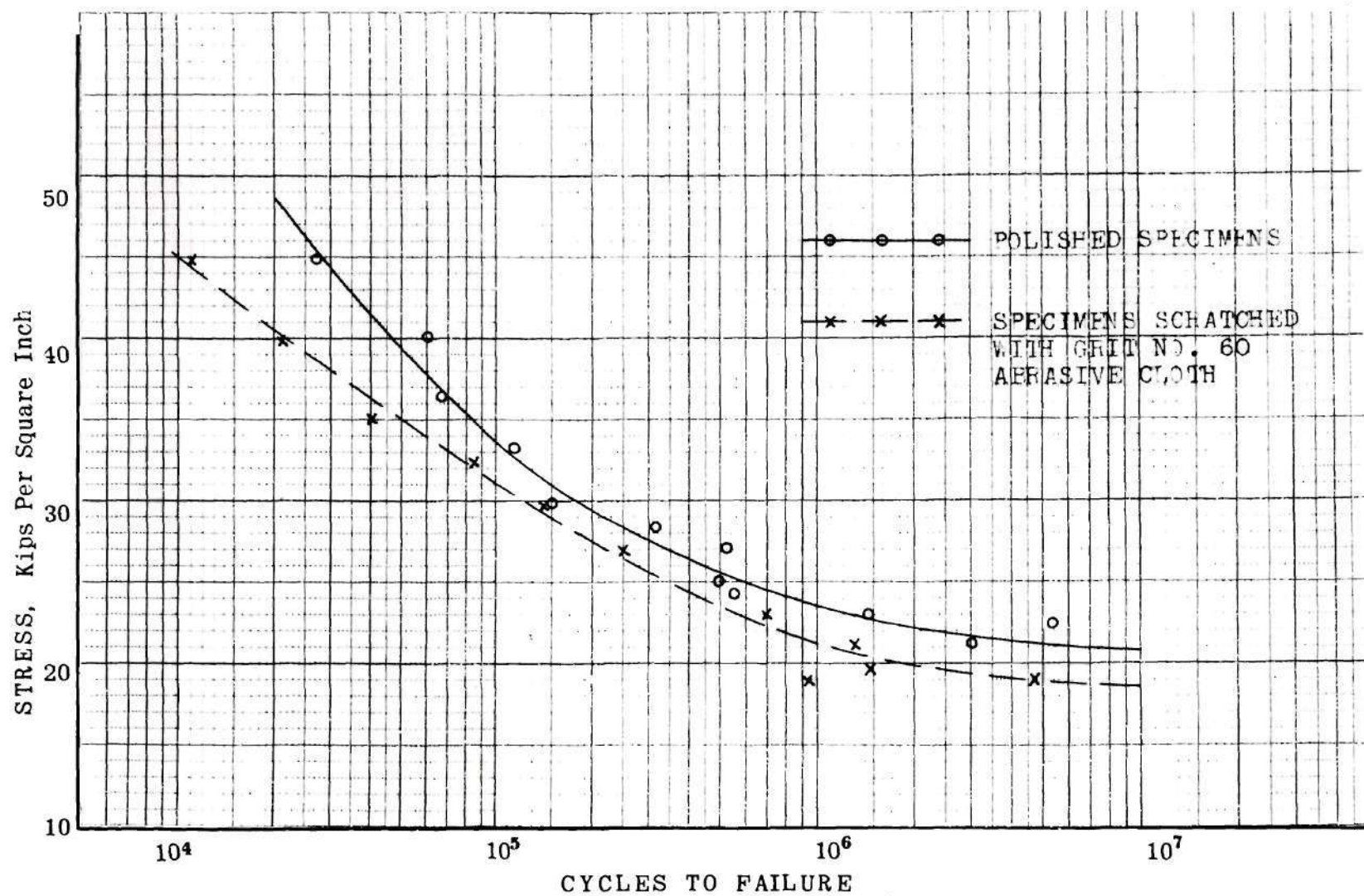


FIGURE 20. FLEXURE FATIGUE STRENGTH OF 0.0395 INCH

24S-T3 SHEET

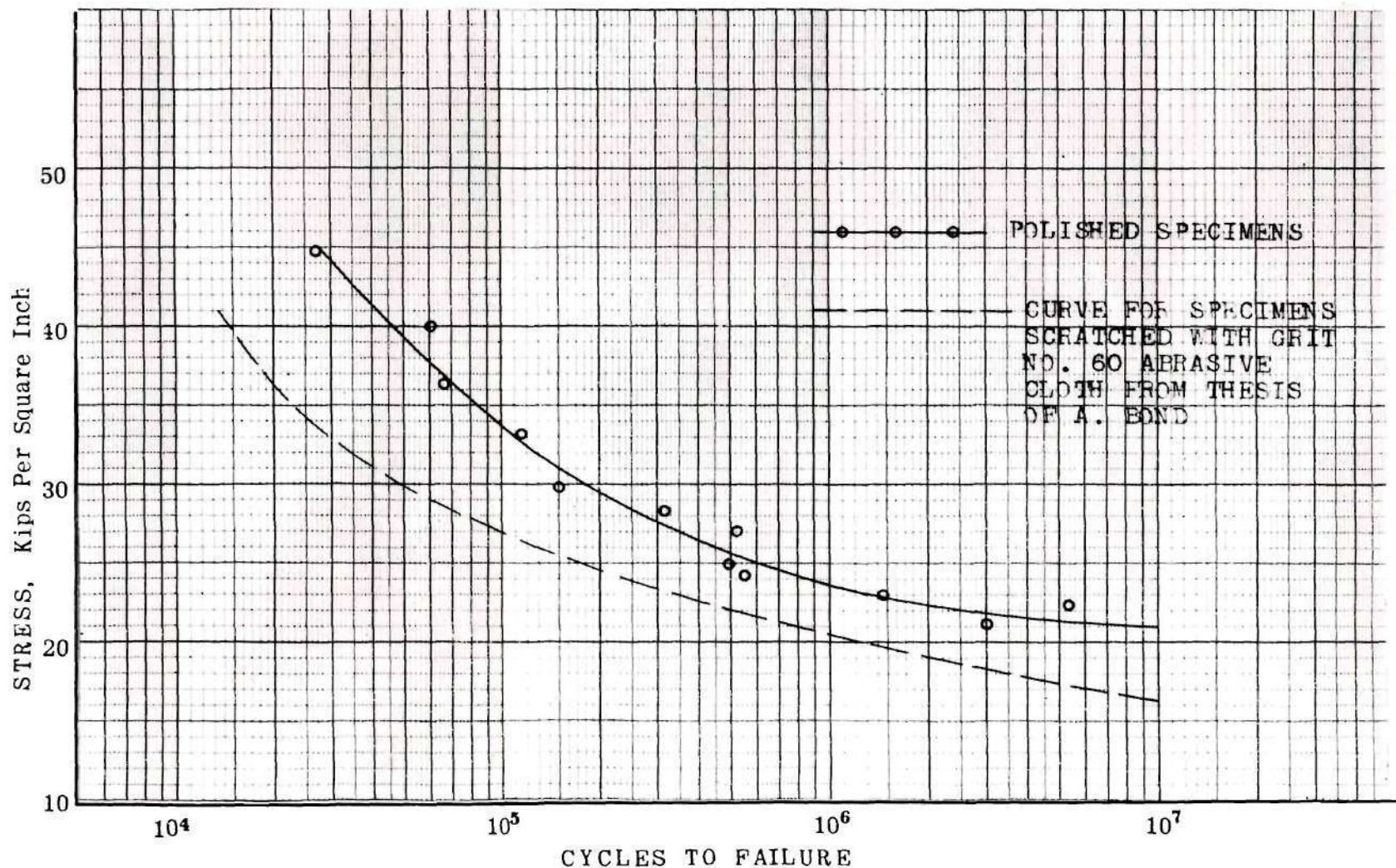


FIGURE 21. FLEXURE FATIGUE STRENGTH OF 0.0395 INCH 24S-T3 SHEET